Eos

VOL. 103 | NO. 4
APRIL 2022

SCIENCE NEWS BY AGU

Planetary Dunes

River Lessons from Mining Mishaps

Seismically Swaying Matterhorn

VERDANT AMAZONIA

Dust and detritus are surprising sources of nourishment for one of the most imperiled places on Earth.

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Dust in the Wind, Dirt Under Our Feet, and Dunes of Another World

I always look forward to what I'll learn in each new *Eos* issue, as much as I hope all of you do. This month, I was fascinated to find out that the Amazon Tall Tower Observatory (ATTO) is, as its name humbly implies, the tallest structure in South America—at 325 meters, it overtops even Paris's Eiffel Tower by a full meter.

The ATTO helps scientists study the dust (drifting over from the Sahara desert) that provides nutrients to the Amazon basin. In "Africa's Earth, Wind, and Fire Keep the Amazon Green," on page 22, read more about how the extreme ecosystems—the world's largest tropical rain forest and the world's largest hot desert—are connected. Researchers are learning more about how changing smoke and wind patterns will affect these climates.

Our April issue is all about the Amazon, and we drift from the wind down into the soil in "The Nutrient-Rich Legacy in the Amazon's Dark Earths," on page 30. It seems rare to learn about human impact—and by that I mean our famous ability to create garbage wherever we are—that leaves an environment better than how we found it.

Terra preta soils, which most researchers call anthrosols due to their origins, are one fascinating example of such an instance. Although terra preta has been identified on several continents, it's been found widely at hundreds of archaeological sites in the Amazon basin. Geologists, soil biogeochemists, paleoecologists, ethnoecologists, and archaeologists from around the world have worked with Indigenous colleagues to study how this "extraordinarily fertile" soil came to be and, perhaps, how it could be replicated today.

More than the Amazon, you might say we have a bit of a landscape theme this month, as we leave Earth for a moment to study the ripples on Mars. Timothy N. Titus and colleagues wrote "Planetary Dunes Tell of Otherworldly Winds," on 36, and you must head over not only for their fascinating descriptions but also for the beautiful images of these formations.

We're pleased to cap off April with another crossword brainteaser from our friend Russ Colson.

Heather Goss, Editor in Chief

Eos

AGU ADVANCING EARTH AND SPACE SCIENCE

Eos: Science News by AGU (ISSN 0096-3941) is published monthly except December by the American Geophysical Union, 2000 Florida Ave., NW, Washington, DC 20009, USA. Periodical Class postage paid at Washington, D.C., and at additional mailing offices. POSTMASTER: Send address changes to *Eos: Science News by AGU*, Member Service Center, 2000 Florida Ave., NW, Washington, DC 20009, USA

Member Service Center: 8:00 a.m.–6:00 p.m. Eastern time; Tel: +1-202-462-6900; Fax: +1-202-328-0566; Tel. orders in U.S.: 1-800-966-2481; service@agu.org.

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Forest Recovery in the Amazon Is a Slow Process

Forest recovery is an important tool for fighting climate change. Recent research, however, shows that recovery in the Amazon has a long way to go to become truly effective.

Secondary forests—wooded areas intentionally replanted after a timber harvest has destroyed a primary or old-growth forest—are one way communities and businesses have responded to deforestation. The trees and shrubs in secondary forests do not entirely replace the trees lost in primary forests, but the plant biomass acts as a carbon sink that offsets carbon emissions associated with the initial deforestation.

According to a new study, however, secondary forests have offset less than 10% of deforestation-caused carbon emissions in the Amazon—even as they take up almost 30% of the total deforested area in the region. With territory accounting for about 60% of the biome, Brazil leads the trend: The country had the lowest carbon offset rate (9%) and the smallest forest area recovery (24.8%).

"Now that there's data available to all individual countries in the Amazon, they don't need to make estimates based [solely] on Brazilian findings."

On the opposite end of the spectrum, Ecuador had the largest forest area recovery (56.9%), whereas Guyana had the highest carbon offset rate (23.8%). These countries, however, represent a small fraction of the Amazon, as they account for just 1.5% and 3%, respectively, of the biome.

The study, published in *Environmental Research Letters,* is the first to analyze forest loss and recovery at both national and subnational levels for the whole Amazon region (bit.ly/secondary-forest-recovery). The researchers analyzed data from all nine Amazonian countries (Bolivia, Brazil, Colombia, Ecuador, France (through the department of French Guiana), Guyana, Peru, Suriname, and Venezuela) and the nine Brazilian states that make up the biome (Acre, Amapá, Amazonas, Maranhão, Mato Grosso, Pará, Rondônia, Roraima, and Tocantins).

The analysis built on land cover data from the Brazilian Annual Land Use and Land Cover Mapping Project (MapBiomas) between 1985 and 2017, as well as on estimates of aboveground biomass and carbon sequestration rates for the period.

The team used MapBiomas remote sensing maps for each year, looking pixel by pixel for areas that were covered and not covered by vegetation to track changes in land use. "We overlapped the maps looking for where there was vegetation in a given year but not in the next, meaning the area was deforested, and where the opposite happened, meaning there was forest recovery," explained coauthor Erika Berenguer, a researcher at the University of Oxford and Lancaster University in the United Kingdom.

"The resolution of each pixel is 30 square meters, so MapBiomas gave us quite fine-grained material to work on," said lead author and Lancaster University researcher Charlotte Smith. Besides fine resolution, the study gives a good picture of what is happening in the whole biome, she said. "Now that there's data available to all individual countries in the Amazon, they don't need to make estimates based [solely] on Brazilian findings."

International and Interstate Disparities

Brazilian states account for more landmass in the region and for a larger share of deforestation. Researchers found that by 2017, the deforested area in Pará alone—more than 260,000 square kilometers, an area larger than the U.S. state of Oregon—was more than twice the cleared area of all other Amazonian countries combined. Deforestation-related carbon emissions from Mato Grosso, Pará, and Rondônia surpass those of any other individual Amazonian country.

Contrasts are also stark among Brazilian states themselves. Whereas Tocantins lost more than 80% of its primary forest and less than 20% of this area was recovered with secondary forest, Amapá had only 4% of its total forest area razed and recovered almost 70% of it with secondary forest. Amapá also managed to offset more than a quarter of its deforestation emissions (26.9%), whereas Tocantins offset only a little more than a tenth (13%).

It is worth noting that Amapá has more than 4 times the forest area of Tocantins, and more than 70% of its area is protected as conservation units or Indigenous lands. The state has the lowest deforestation rates in the Brazilian Amazon according to the Amazon Deforestation Monitoring Project, part of Brazil's National Institute for Space Research.

Older Forests Have Greater Carbon Sequestration

University of Connecticut professor Robin Chazdon, who did not take part in the study, said it confirmed trends observed in previous research about carbon recovery in reforested regions. "It also shows the need for deeper analysis of the economic, social, and political factors that are part of these trends," she said.

Chazdon explained that the amount of remaining forest in a place is a predictor for unassisted vegetation regrowth. "Sometimes

there's a time lag between forest clearance and land use," she said, hinting that older secondary forests may yield higher carbon sequestration rates.

The numbers in the study back Chazdon's observations: Almost 80% of all secondary forest vegetation analyzed was less than 20 years old, with an average age of 8 years. Guyana and Suriname had some of the oldest secondary forests studied, and these countries had the highest carbon recovery rates of the whole biome.

"We're always told the story of how we are failing the Amazon forest. But places like Ecuador and Amapá show that the Amazon is not all about failure."

"This means that trees must be given time to grow, so their carbon absorption can make some difference," Berenguer said. She stressed that secondary forests are not absorbing as much carbon as they could for two primary reasons: Deforestation emissions in the Amazon are still overwhelmingly high, and at the same time, secondary forests are razed at a young age across most of the biome. "It is counterproductive to plant a hectare and tear another 10 down," she added.

Despite the scenario, the researchers see some space for hope. "We're always told the story of how we are failing the Amazon forest. But places like Ecuador and Amapá show that the Amazon is not all about failure. They're two cases that need to be looked at in detail so we can learn something that can be useful to the whole biome," Berenguer said.

"Latin America has the highest forest recovery capacity in the world, with the Amazon forest having the highest potential across the region," said Chazdon. "Brazil is the single country with the highest forest recovery capacity in the world—but social, economic, and political factors impede regrowth."

By **Meghie Rodrigues** (@meghier), Science Writer

What a Gold Mining Mishap Taught Us About Rivers

In 1900, gold miners blasted a hole in a ridge to reroute the North Fork Fortymile River. Instead of flowing around a bend for more than 3 kilometers, the river, seen here in 1975, gushed over a 6-meter waterfall in a 30-meter span. In the century since, the formidable cascade has eroded into a series of rapids that boaters can navigate. Credit: U.S. National Park Service

What a disappointment it must have been: Just 1 year after miners in southeastern interior Alaska blasted through a ridge to redirect a tributary of the Yukon River, they abandoned the site, leaving a drastically changed waterway.

Instead of flowing around a more than 3-kilometer meander, the North Fork Fortymile River cut directly through a 30-meter ridge. Miners deserted the site in 1901, wrote local historian Elva Scott, because a landslide covered their mining site just 1 year after the blast.

But U.S. Geological Survey geomorphologist Adrian Bender said the debacle kicked off a perfect scientific experiment.

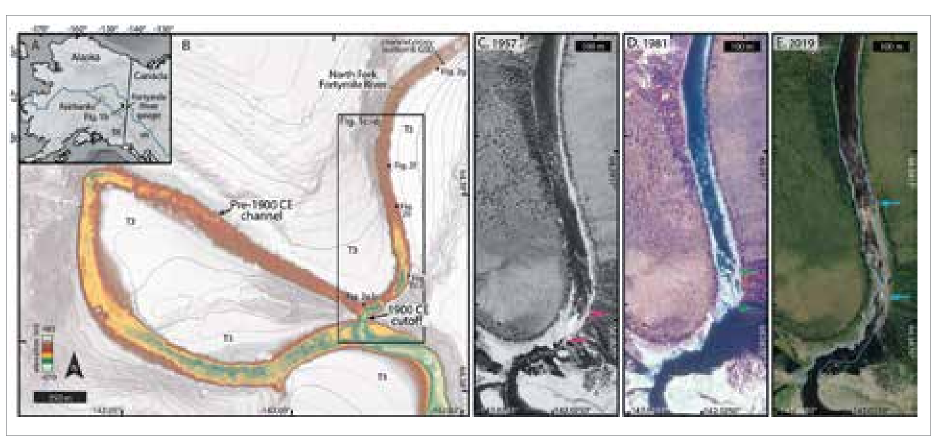
"As a scientist thinking about how the river responds, it couldn't be more perfect that the miners would make this massive change and then just walk away within a year," Bender said.

Geomorphologists often arrive long after nature's forces have been at work. But Bender found historical observations and photographs of the canyon going back to 1900, when the blast occurred. Along with measurements taken in 2018, these made it possible to document the river cutting into the bedrock in real time over the intervening 119 years.

The work revealed how rivers change the way they sculpt the landscape even on short timescales, said Brian Yanites, a geomorphologist at Indiana University Bloomington who was not involved in the work: "What [Bender] documents in 100 years would take a river in the most dynamic landscapes many millennia to erode."

A Canyon's Life

In 1900, gold miners working for an English investment corporation set off dynamite to blow a 5-meter gap in a 30-meter ridge. The site, now called The Kink in the U.S. National Register of Historic Places, sits on the traditional land of the Hän and Dënéndeh people.



(a) The point where the North Fork Fortymile River was rerouted, (letter B) sits near the Canadian border. (b) A map of the river shows the original meander and the short new channel cut by the miners. (c–e) Satellite images reveal the location of the knickzone (arrow) over time. Credit: Bender, 2021, https://doi.org/10.1130/G49479.1

Compared with 119 years ago, the 30-meter waterfall has transformed into a 500-meter-long series of rapids that flow through a high-walled canyon. Credit: Adrian Bender/USGS

Within hours of the explosion, the river abandoned the old channel and rushed down the new one, tearing at the bedrock and more than doubling the size of the gap.

"It couldn't be more perfect that the miners would make this massive change and then just walk away within a year."

Over the next century, the new channel would morph from a waterfall into a series of rapids and would reveal how bedrock canyon incision works.

In the first 3 years of its life, the channel changed rapidly. The waterfall—also referred to as a knickzone (an unusually steep section of a river)—moved upstream at a quick clip of 23 meters per year on average.

Over the next 80 years, the waterfall flattened out into a series of rapids and only slowly moved upstream (about 4 meters per year on average). Since the 1980s, the base of the knickzone has stalled, but the top has continued to move upstream, said Bender, who published the work in the journal *Geology* (bit.ly/the-kink).

The river's changes reveal underlying forces at work. When the new channel first formed, it was so steep that it carried mailbox-sized rocks downstream with ease. The debris battered the canyon's crystalline bedrock, scouring the channel drastically. Its slope decreased fourfold over the first 60 years.

Once the river became less steep, erosion continued, but the process behind it changed. Before, the steepness of the waterfall brought boulders to erode its bank. Now, the flow of the river must be above average to carry large rocks to chip away at the channel.

Scientists use the terms transport limited and detachment limited to compare these two types of river processes, and the latest work shows how one river can transition from one type (detachment limited) to another (transport limited) after a significant event.

Understanding how canyons form can help scientists interpret faults or earthquakes. With the right information, researchers could explain how recent uplift happened at a fault, for instance, by looking at the shape of a river canyon that bisected it. In Taiwan, an earthquake in 1999 boosted one side of a river by two stories, causing the channel to slice a 1,200-meter-long gorge in the Da'an River.

"Rivers are the agents of erosion and sediment transport," Bender said. "Understanding how rivers do that work is fundamental to understanding how landscapes change over time."

By **Jenessa Duncombe** (@jrdscience), Staff Writer

Coal Seam Fires Burn Beneath Communities in Zimbabwe

Coal fires can smolder for decades underground. Credit: Henrique Sá/Unsplash

As Zimbabwe's coal industry expands, residents around the western town of Hwange are experiencing the effects of underground coal seam fires. Residents, particularly children, and livestock are at risk of falling into smoldering fires beneath unstable ground. Unfenced areas above the fires are often used as outdoor toilets, playgrounds, and grazing areas. Victims suffer burned legs, and in one case, a young girl died of her burn injuries.

"The [Hwange] community is living in fear of these fires, as the number of people getting burned increases with each passing day. Livestock, especially in the Madubasa area [in Hwange], have also fallen victim to these fires," said Fidelis Chima, coordinator of Greater Whange Residents Trust.

Most of these fires start with the ignition of exposed coal seams, but they can also spark in coal storage or waste piles. Coal seam fires, which can ignite naturally as well as through human activity, can burn for decades and even thousands of years. Thousands of fires are burning at any given time around the world, releasing toxic fumes that account for 3% of the world's carbon emissions and release 40 tons of mercury into the atmosphere every year.

A report by the Centre for Natural Resource Governance, an environmental organization based in Zimbabwe, revealed that the underground coal fires in and around Hwange have left some residents with "near-death experiences and permanent disabilities" (bit.ly/coal-fires).

"The main challenge is that no one really knows the extent of the coal seam fires."

"We have so far recorded seven cases of severe coal fire injuries, of which one ended in fatality," said Farai Maguwu, director of the Centre for Natural Resource Governance. Worse, he said, "no one really knows the extent of the coal seam fires. Often residents are only alerted through a disaster."

Working with Industry to Find a Solution

The Hwange Colliery Company Limited (HCCL), a coal mining and production company in Zimbabwe, said it is addressing threats associated with the coal seam fires by working with industry professionals and local communities.

HCCL managing director Charles Zinyemba said public awareness campaigns are regularly carried out in schools and villages in the area. "Tribal elders were engaged to assist in disseminating this information to the villagers. Communities in close proximity to the affected areas were and will continue to be informed of temporary measures to manage risks such as road diversions...as well as placement of signage at the affected areas," he said in a statement.

Zinyemba also said HCCL had hired a German company, DMT, to help with subsurface fire detection (including magnetic mapping) and extinguishing. The company also invested in a drone equipped with a thermal imaging camera, which it will use for security purposes and for underground fire detection. "We have confidence that put together, all the above interventions will soon absolutely contain the spontaneous fires, all in the best interest of the Hwange citizenry and related stakeholders," Zinyemba said.

Chima said the Greater Whange Residents Trust was working closely with both HCCL and Zimbabwe's Ministry of Environment to find a solution to the underground fires. "As an organization, we will be playing a monitoring role."

Maguwu acknowledged that awareness campaigns, as well as industry resolve, are critical in fighting the fires. "This should be done through local radio, social media, public meetings, and schools. But the HCCL also needs to invest in technology so as to detect the fires and then take measures to erect fences and danger warning signs," he said.

The report from the Centre for Natural Resource Governance noted that "some of the victims who are now adults were injured whilst young and had their future ruined by the permanent injuries, lengthy periods spent in hospitals and unending excruciating pain.... The children who fall victim to the coal seam fires suffer a range of physical and psychological effects which include post-traumatic stress disorder (PTSD)."

Maguwu said HCCL must assist victims with medical costs, rehabilitation, and life skills to ensure that they overcome these disabilities.

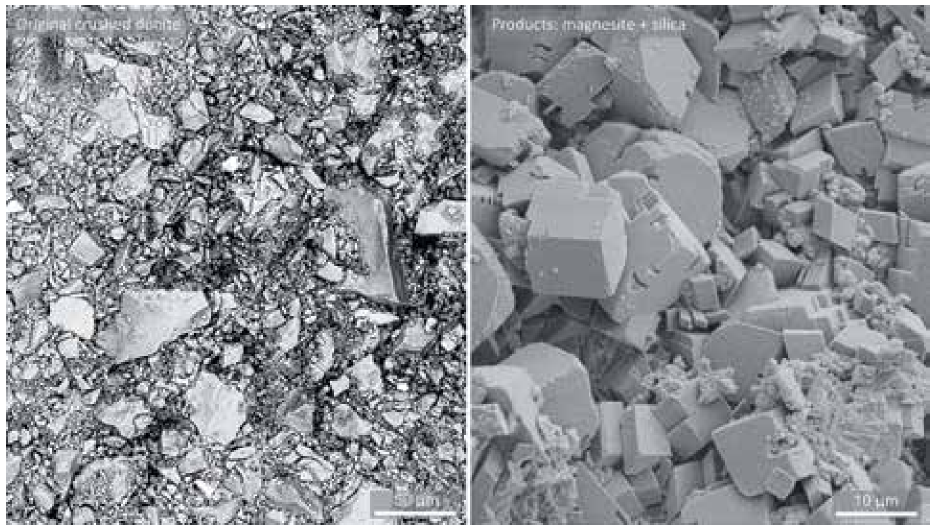
By **Andrew Mambondiyani** (@mambondiyani), Science Writer

Good News: Rocks Crack Under Pressure from Mineral CO_2 Storage

As concentrations of atmospheric carbon dioxide (CO_2) continue to rise and drive climate change, scientists have been researching options not just to reduce CO_2 emissions but also to remove carbon from the atmosphere. Many carbon capture and storage methods seek to trap gaseous or water-dissolved CO_2 in underground storage reservoirs, but these could leak and release greenhouse gases back into the atmosphere.

"When you inject CO_2 in a gas form, it can escape, for example, if a fault is moving or there is damage to the reservoir. It is always going to be looking for a way to escape to an area where the pressure is lower," explained Catalina Sanchez-Roa, an experimental geophysicist at Columbia University Climate School in New York City. "But with carbon mineralization, you [store] it as a mineral, as a solid, and then it's very stably stored for a really long period of time."

With mineral carbon storage, CO_2 dissolved in water chemically reacts with rocks to form new minerals with the carbon. This process occurs all the time in nature and stores carbon within solid minerals for hundreds or thousands of years with little risk that it will escape back into the atmosphere. The downside? Storage capacity is limited. The carbonized water has to seep into the stone, but the mineralization process tends to clog up the pathways and reduce a rock's permeability. Eventually, water can't reach new surface areas to react with.



Scanning electron microscope images show slices of a dunite sample before and after the injection of dissolved carbon dioxide. Before injection (left), the sample comprises mostly jagged olivine crystals roughly 50 micrometers (µm) in size. After injection and the subsequent carbon mineralization (right), the olivine transformed into blocky magnesite crystals 10 micrometers or smaller and tiny amorphous silica minerals. Credit: Catalina Sanchez-Roa

Cracking extended the duration of the reaction and enhanced the rock's carbon storage capacity.

In new laboratory experiments, Sanchez-Roa tested how the permeability of dunite changed during a month of carbon mineralization. After an initial period in which mineralization clogged things up as expected, the mineralization created new fractures in the rock that exposed more reactive surface. The cracking extended the duration of the reaction and enhanced the rock's carbon storage capacity. Sanchez-Roa presented these results at AGU's Fall Meeting 2021 (bit.ly/peridotite-carbon-storage).

Make Way for Magnesite

To store carbon, a rock's geochemistry has to be able to take the carbon from CO_2 molecules and turn it into a mineral. Olivine minerals, which are common in igneous rocks, are very good at doing this. Carbon mineralization experiments focus on ultramafic, olivine-rich materials like basalt and dunite, which are found in land-based and seafloor deposits. For the purposes of carbon capture and storage, carbon mineralization is "just enhancing a process that happens naturally in many parts of the world," Sanchez-Roa said.

In her experiments, Sanchez-Roa first created a dunite aggregate made from natural rocks that had been ground down to a known grain size, which made for more controlled testing. She injected the samples with carbonized water and monitored their permeability by precisely measuring fluid flow. Some experiments lasted only 4 days, and others went as long as 35 days.

The dunite's olivine (Mg_2SiO_4) reacted with the injected CO_2 to form silica (SiO_2) and magnesite ($MgCO_3$). At the beginning, the carbonized minerals began clogging up the rock and reducing permeability. But because the end products took up more volume than the original material, the magnesite and the silica ran out of empty space inside the rock even as new crystals kept forming. The carbonate minerals started pushing outward, trying to create more room to fit, and ultimately created cracks in the dunite sample.

"Even though the permeability was really low already, [cracking] kept some fluid going through it," Sanchez-Roa said. "And it kept cracking, which means that some of the reaction was still happening and some of the CO_2 was being captured." The rock actually became slightly more permeable for a short while, which was interpreted as fractures being created. The increased permeability meant that the sample could mineralize more carbon than it could have without the cracking. To see the carbon reaction continue after 35 days "is pretty amazing. It is the first time that we have seen the cracking happening in experiments."

This work "contributes to answering a critical question: Is underground CO_2 storage safe?" said Amir Jahanbakhsh, a petroleum

Olivine-rich dunite is a promising candidate for long-term carbon dioxide storage. Credit: James St. John, CC BY 2.0 (bit.ly/ccby2-0)

reservoir engineer at Heriot-Watt University in Edinburgh, U.K. Jahanbakhsh was not involved with this research. "We need to integrate petrophysics, geomechanics, and geochemistry to understand petrophysical and mechanical changes of porous media as a result of chemical reactions happening due to CO_2 injection."

Scaling It Up

Some field testing of carbon mineralization in basalt is already ongoing, but there is still a lot of research needed into how well the process works with different types of stone and under various conditions before it can be engineered into a large-scale carbon storage solution.

When selecting sites for in situ mineralization, "it is essential to understand the geochemistry of the system first," Jahanbakhsh said. "We need to investigate whether these mechanisms have altered the petrophysical and mechanical properties of the storage medium to conclude that CO_2 storage is safe for a site of interest."

To that end, Sanchez-Roa's future experiments will explore dunite mineralization at different temperatures, with natural unprocessed rocks instead of aggregates, and with a focus on the solid products that are produced. "We're finding new things every time that we do an experiment," she said. "And now we're hoping to find a way to optimize this process so we can help implement more pilot projects around the world."

By **Kimberly M. S. Cartier** (@AstroKimCartier), Staff Writer

Mountains Sway to the Seismic Song of Earth

From a human perspective, mountains stand stoic and still, massive symbols of quiet endurance and immovability.

But new research reveals that mountains are, in fact, moving all the time, swaying gently from the seismic rhythms that course through the earth upon which they rest.

A recent study published in *Earth and Planetary Science Letters* reports that the Matterhorn, one of the most famous mountains on the planet, is constantly vibrating, about once every 2 seconds, because of the ambient seismic energy originating from earthquakes and ocean waves around the world (bit.ly/moving-matterhorn).

"It's kind of a true song of the mountain," said Jeffrey Moore, a geologist at the University of Utah and senior author of the study. "It's just humming with this energy, and it's very low frequency; we can't feel it, we can't hear it. It's a tone of the Earth."

Recording the "Song of the Mountain"

Every object "wants" to vibrate at certain frequencies depending on its shape and what it is made of (a property known as resonance). Familiar examples include tuning forks and wine glasses; when energy of a resonant frequency hits the object, it shakes harder. Moore and his colleagues hypothesized that mountains, like tall buildings, bridges, and other large structures, also vibrate at predictable resonances on the basis of their topographic shape.

Scientists placed a solar-powered seismometer near the summit of the Matterhorn to record ambient seismic vibration data. Credit: Jan Beutel/ETH Zurich

But unlike the world of civil engineering, in which one can test what frequencies are resonant by placing large shakers on the structure or waiting for vehicles to drive over them, it would be impractical to excite something so large as a mountain.

Instead, Moore and his international team of collaborators sought to measure the effects of ambient seismic activity on perhaps one of the most extreme mountains: the Matterhorn.

Located on the border of Italy and Switzerland in the Alps, the pyramid-shaped Matterhorn is the most photographed mountain in the world. It towers nearly 4,500 meters

"It's kind of a true song of the mountain. It's just humming with this energy, and it's very low frequency; we can't feel it, we can't hear it. It's a tone of the Earth."

(15,000 feet) in elevation, and its four faces point in the cardinal directions.

Researchers helicoptered up the Matterhorn to set up one solar-powered seismometer roughly the size of a "big cup of coffee" at the summit. Another was placed under the floorboards of a hut a few hundred meters below the peak, and a third was placed at the foot of the mountain as a reference, said Samuel Weber, a researcher at the Institute for Snow and Avalanche Research in Switzerland and lead author of the study.

The seismometers continuously recorded movements and allowed the team to extract the frequency and direction of the resonance.

The movements were small, on the order of nanometers at the baseline to millimeters during an earthquake, Moore said. "But it's very real. It's always happening."

The measurements showed that the Matterhorn consistently oscillates in the north-south direction at a frequency of 0.42 hertz, or slightly less than once every 2 seconds, and

in the east-west direction at a similar frequency.

Comparing the movement on top of the mountain with measurements from the reference seismometer at its base, the researchers found that the summit was moving much more than the base.

"It was quite surprising that we measured movement on the summit that was up to 14 times stronger than next to the mountain," said Weber.

The researchers also made measurements on Grosser Mythen, a similarly shaped (albeit smaller) Swiss mountain, and found similar resonance.

"I just think it's a clever combination of choices in terms of the location being so iconic and the careful placement of instruments," said David Wald, a seismologist with the U.S. Geological Survey who was not involved in the study. Choosing a smooth mountain like the Matterhorn also removed the problems brought by soil and sediment, which would have added another layer of complexity to measuring movement.

Researchers install the reference station at the foot of the Matterhorn in the Swiss Alps. Credit: Jeff Moore/ University of Utah

What Makes the Mountains Hum

The baseline vibrations of mountains like the Matterhorn are caused by the hum of seismic energy.

"A lot of this comes from earthquakes rattling all over the world, and really distant earthquakes are able to propagate energy and low frequencies," Moore said. "They just ring around the world constantly."

But the data also pointed to another, unexpected source: the oceans.

Ocean waves moving across seafloors create a continuous background of seismic oscillations, known as a microseism, which can be measured around the world, Moore said. Intriguingly, the microseism had a frequency similar to the resonance of the Matterhorn.

"So the interesting thing was that there's… some connection between the world's oceans and the excitation of this mountain," Moore said.

The research has practical applications in understanding how earthquakes could affect steep mountains where landslides and avalanches are a constant worry.

It also brings to life a new way of appreciating the Matterhorn and all other mountains swaying in their own way to music hidden deep within Earth.

"You come to one of these landforms with this idea that you're trying to capture something hidden, something new and unknown about it," Moore said. "It's actually a lot of fun because it makes you sit up quietly and think about the mountain in a different way."

By **Richard J. Sima** (@richardsima), Science Writer

A Giant Impact Triggered Earthquakes for Thousands of Years

Every few hundred million years, give or take, our planet is pummeled by a kilometer-scale chunk of rock. These rare, but cataclysmic, impacts are known to have altered ecosystems and caused widespread extinctions. Now, researchers have shown that such events can also trigger earthquakes that persist for thousands of years. This discovery, made at the Vredefort impact structure near Johannesburg, South Africa, sheds light on how the planet's crust reequilibrates after a massive impact, the team suggested.

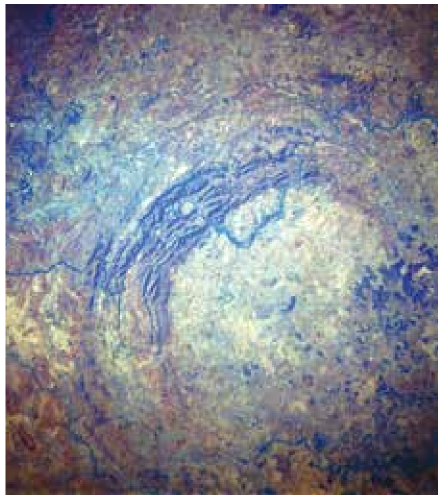
A Look Beneath

The Vredefort impact structure is the world's largest extraterrestrial scar. But because of its pronounced age—2.02 billion years, to be precise—the original crater is no longer visible. The cumulative effects of erosion from water, wind, and ice over geologic time have stripped away roughly 10 kilometers' worth of material, said Matthew S. Huber, a geologist at the University of the Western Cape in Cape Town, South Africa, and lead author of the study (bit.ly/Vredefort-impact). "What we're looking at now is what the structure looks like very deep below the impact."

"What we're looking at now is what the structure looks like very deep below the impact."

That's a unique vantage point, said Huber. "We don't have any other large impact craters where we get to see what it looks like when you slice into it."

Taking advantage of that perspective, Huber and his colleagues studied several of the impact melt dikes within the Vredefort impact structure. These vertically oriented slabs of rock crosscut through the region's granites. They likely consist of impact melt, an amalgam of once molten material that pooled at the planet's surface shortly after the cataclysm, previous studies have suggested (bit.ly/Vredefort-structure). And because these dikes are still visible today



Geological evidence suggests that earthquakes reverberated for tens of thousands of years after an asteroid struck South Africa. Credit: NASA/STS51I-33-56AA

despite extensive erosion, impact melt must have traveled far below the surface, the researchers surmised. "Why do we have these dikes deep in the subsurface? That's the overarching research question," said Huber.

Rebounding Crust

The opening of fractures in Earth's crust—associated with earthquakes—could have plausibly allowed these dikes to extend to great depths, previous research has noted (bit.ly/dikes-extend). Seismic activity makes sense because of the titanic forces at play in the wake of the impact, said Huber. The impact scraped away kilometers of sediments nearly instantaneously, and the planet's crust would have rebounded in response. "This is the same as if you have a glacier that's retreating—the land is rising up again after the glacier has moved away," he said. "It's the same type of isostatic rebound."

But the duration of such ground shaking has never been constrained. That's an important quantity to understand, Huber and his collaborators noted, because it gets at a fundamental question: Is an impact event a one-and-done affair, or do aftereffects continue to roil a region for some time?

"Crustal settling over geologic time has always been suspected around large impact basins, but the duration of that settling has been elusive," said David Kring, a planetary geologist at the Lunar and Planetary Institute in Houston not involved in the research. "The current paper attempts to resolve that issue."

A Striking Boundary

Huber and his colleagues studied five dikes. Three appeared to be homogeneous across their exposed faces. But the remaining two stood out, even at first glance: Their interiors were dark brown, and their peripheries tended to be lighter in color and flecked with beige. "The boundaries between the phases are quite sharp—you can put your finger on the precise contact between them," Huber told *Eos.*

Back in the laboratory, the researchers found that the two visually striking dikes were, indeed, chemically inhomogeneous: Their interiors contained a higher fraction of iron and magnesium, and their peripheries tended to be dominated by silicon and potassium. This finding suggests that two chemically distinct pulses of impact melt poured downward to form these dikes, Huber and his colleagues surmised. That's possible only if the melt sheet chemically differentiated between the two pulses, the researchers concluded, which in turn implies that some interval of time separated episodes of ground shaking.

The Reign of Earthquakes

The first downpouring of impact melt must have occurred before the melt sheet differentiated, and the second had to have taken place after differentiation but before the melt sheet solidified, the researchers reasoned. On the basis of previous estimates of the timing of those events made by other researchers, Huber and his colleagues concluded that earthquakes shook the region for at least tens of thousands of years.

This finding reveals the enduring nature of massive impact events, said Huber. "It is not simply a moment in time. Even tens of thousands of years after an impact, you would not want to be building a house on the periphery of a crater."

By **Katherine Kornei** (@KatherineKornei), Science Writer

A New Explanation for Organics on a Mars Rock That Fell to Earth

Numerous stories have put Martians at the forefront of science fiction, but we can thank one 4-billion-year-old rock for placing life on Mars into the realm of serious scientific discourse. That rock is the meteorite Allan Hills 84001 (ALH84001).

When scientists found evidence of organic molecules in ALH84001, some asserted that these remnants were indications of past life on Mars. This hypothesis drew intense skepticism, with many scientists identifying the molecules as contamination from Earth. Others maintained that a portion of the molecules—the meteorite's polycyclic aromatic hydrocarbons (PAHs)—were Martian, whereas others found similar PAHs on Earth. Many scientists argued that abiotic processes, not life itself, could easily account for PAHs and other organics in the meteorite.

Nearly 30 years after the meteorite's discovery, ALH84001's organic molecules still fuel scientific inquiry. A new study, led by astrobiologist Andrew Steele at the Carnegie Institution for Science, inferred the geochemical environment of early Mars and the origins of ALH84001's organics. The research was published in *Science* (bit.ly/early-Mars-organics).

Serpentinization and Primordial Soup

Steele's team found evidence supporting the idea that the organics inside ALH84001 are from Mars. When measuring the hydrogen isotope ratios of the organics and weathered minerals, for instance, the team found that the ratio of heavy to light hydrogen matched that measured in water found on Mars's crust.

When examining the mineral composition of ALH84001, Steele's team found minerals similar to serpentine and talc on Earth. Such minerals are products of a process called serpentinization, which happens when ultramafic rocks react with water. This process results in heat and hydrogen gas, which can then reduce inorganic carbon (such as carbon dioxide and carbon monoxide) to methane and other organic molecules.

The study showed that "Mars can undertake the chemistry that eventually led to life."

From these data, Steele's team hypothesized that serpentinization occurred in Mars's past and likely led to the synthesis of the organic molecules in ALH84001. The study showed that "Mars can undertake the chemistry that eventually led to life," he said. "What we found in the meteorite is a cache of nonlife-synthesized material made [on Mars] that could contribute to a potential Martian primordial soup."

"I think [the study] very nicely...shows evidence of serpentinization as a process to create the minerals in the rock," said Jennifer Glass, an astrobiologist and biogeochemist at the Georgia Institute of Technology who was not involved in the research.

Analogues on Earth

This evidence of serpentinization opens new doors to the possibility of Mars having once been habitable. Around 4 billion years ago, Mars's geochemical environment may have resembled the conditions of Earth around the time life arose.

In fact, hydrothermal serpentinizing environments have been proposed as the birthplace of Earth's first life-forms. The hypothesis is that "the origin of life started as a complex set of chemical reactions that took place at hydrothermal vents," explained Luther Beegle, a physicist turned astrobiologist at NASA's Jet Propulsion Laboratory who was not involved in the study. Steele and colleagues' study "shows that there is the possibility of serpentinization happening long enough to generate enough organic material so that life could have conceivably originated [on Mars]."

Jeffrey Seewald, a geochemist at Woods Hole Oceanographic Institution who was not involved in the research, agreed. "To me, [this finding] is a particularly important contribution [of the study].... Fluid-rock reactions, especially serpentinization, can create habitable environments by providing a source of chemical energy that can be used by microorganisms."

The study presented compelling evidence that may hint at how life could have feasibly started on Mars from abiotic processes. But the research does not solely teach us about other worlds, said Steele; it also supports some ideas about the evolution of life here on Earth. The processes that may have contributed to organic molecules on Mars also may have been present on Earth. The study is "not just about, 'Is life out there?' and 'Are we alone?' It's also about, 'Where did we come from?'"

By **Derek Smith** (@djsmitty156), Science Writer

The organic molecules that likely come from Mars are associated with the orange globules in Martian meteorite ALH84001. Credit: NASA/JSC/Stanford University

Himalayas Are Experiencing an "Exceptional" Loss of Glacial Mass

Astronauts aboard the International Space Station captured this image of the Himalayas in 2017. Credit: NASA

Loss of glacial mass in the Himalayas has been "exceptional" when compared with all other regions in the world, a new paper has shown (bit.ly/glacial-loss-Himalayas). The authors mapped 14,798 Himalayan glaciers as they existed during the last period of glacial advance, the Little Ice Age, around 400–700 years ago. They analyzed around 2,300 kilometers of the mountains, ranging from India to Bhutan.

They found that 40% of the glacier area has been lost and that mass loss in recent decades has occured 10 times faster than earlier loss since the Little Ice Age. The greatest glacial mass loss was in the eastern Himalayas, with Nepal and Bhutan experiencing the fastest declines.

Tracking Glacial Loss over Centuries

The study is the first assessment of changes in Himalayan glaciers over a centennial timescale.

Many studies have quantifiably assessed the rate of glacial mass change across the Himalayas for recent decades (bit.ly/Himalayas-ice-loss). But "these are still within the time period of anthropogenic climate change and make no comparison with glacier mass loss before their study time period," said Ethan Lee, a researcher at Newcastle University and lead author of the paper. Studies that have been concerned with glacial mass loss since the Little Ice Age "have either been limited to small regions or watersheds or singular glaciers and cannot be extrapolated to across the Himalaya," he added.

To expand the field of study and get a more holistic evaluation of glacial retreat, the authors aimed to create a data set of glaciers at their Little Ice Age extents and perform glacial ice surface reconstruction to identify the overall mass loss from the Little Ice Age to present.

As for what exactly is driving the exceptional acceleration in glacier mass loss across the Himalayas, Jonathan Carrivick, a senior lecturer in physical geography at the University of Leeds and a coauthor of the study, identified climate change as the "root cause."

Rijan Bhakta Kayastha, coordinator of the Himalayan Cryosphere, Climate and Disaster Research Center at Kathmandu University who was not involved in the new study, agreed. He pointed to a 2017 study by Nepal's Department of Hydrology and Meteorology that found that throughout the country, temperatures increased by 0.056°C per year (bit.ly/Nepal-climate-trend). Another reason for the region's rapid glacial retreat is a lack of corresponding increase in precipitation, Kayastha said. "If temperature and precipitation increase, there could be some balance because of new ice formation. But this is not happening," he explained.

Elaborating on what glacial mass loss means for the people in the region, Kavita Upadhyay, an independent water policy researcher based in the Indian Himalayas, said, "The rapidly melting glaciers will increase flood risk from the breach of glacial lakes, since such lakes will increase in size and number from the fast melting glaciers."

Upadhyay noted that development activities in the Himalayas (like the construction of roads alongside rivers and massive hydropower projects) compound disaster risks. Upadhyay is one of the authors of a June 2021 paper that evidenced how hydropower infrastructure contributed to a disaster in the Himalayan state of Uttarakhand that claimed more than 200 lives (bit.ly/Himalayan-disaster).

Loss of glaciers also contributes to "water insecurity in the long term," Upadhyay said,

as glaciers feed rivers throughout the Himalayas.

Need for Collaboration

In India, there is "no institutional structure for constant dialogue and collaboration" between policymakers and researchers working on glaciers, said Anil V. Kulkarni, a visiting scientist at the Divecha Centre for Climate Change, Indian Institute of Science.

"The rapidly melting glaciers will increase flood risk from the breach of glacial lakes, since such lakes will increase in size and number from the fast melting glaciers."

Speaking of what researchers could do to bridge the gap, Lee said they could better communicate actionable recommendations and make their research more easily accessible so that policymakers could make informed decisions.

Piyoosh Rautela, executive director of the Uttarakhand Disaster Mitigation and Management Center, expressed similar concerns. Policymakers can work only on glacial research that addresses societal implications, he said, but many research papers "focus on hard science and not on actionable inputs." He added that the lack of open access to some journals is "a serious constraint" to both policymakers and researchers working at small institutions. As a path ahead, Rautela suggested early-stage collaboration between researchers and policymakers and not communication only after the research is published.

More broad and important, glaciology is a "multidisciplinary research topic," Kulkarni said. Consistent and structured collaboration at institutional levels is needed, he explained, as opposed to "sporadic efforts by individuals."

Pointing to one area of collaboration, Kayastha said that there is a need for governmental focus on and funding of glacial monitoring at high altitudes across South Asia.

By **Rishika Pardikar** (@rishpardikar), Science Writer

Mining Threatens Isolated Indigenous Peoples in the Amazon

Mining on Indigenous land is currently forbidden in the Brazilian Amazon. However, a bill put forth by the Brazilian government is seeking to change that—and if it succeeds and becomes law, the consequences could be dire for isolated Indigenous Peoples, new research warns.

The bill, PL 191/2020, would expand conditions for carrying out research and mining of mineral and hydrocarbon resources, as well as the use of water resources for energy production, on Indigenous lands. By August 2020, a few months after President Jair Bolsonaro backed the bill, Brazil's National Mining Agency had 3,645 registered mining requests on Indigenous lands with isolated groups in the Amazon. According to the study, published in the journal *Global Environmental Change*, this activity could directly affect more than 10 million hectares, an area 30 times the size of the United States' Yosemite National Park (bit.ly/Brazil-mining).

Even this number might be underestimated, according to lead author Sara Villén-Pérez, a biogeography researcher at the University of Alcalá in Spain. As well as a direct impact, she explained, "mining activities have a great indirect impact over deforestation by stimulating the construction of roads and urban areas to accommodate workers. Some studies estimate that secondary effects could extend for over 70 kilometers (43.5 miles) from the mining site."

Villén-Pérez and her colleagues in Brazil and Spain cross referenced mining requests the National Mining Agency received up to late August 2020 with information on isolated Indigenous groups compiled by the Socio-Environmental Institute, a civil society organization focused on the defense of human and environmental rights in Brazil, and FUNAI, Brazil's National Indian Foundation. The researchers considered mineral prospecting and operation requests.

The team found great overlap between territories with isolated Indigenous groups (those without sustained contact with neighboring communities) and areas with registered interest for mining—almost half the lands with these groups have mining requests. These regions (in the states of Amazonas, Pará, and Roraima) sit on the Guiana and Brazilian shields, which are richer in minerals than other areas in the Amazon basin.

The intersection of mineral-rich areas and Indigenous lands with isolated groups is disastrous, the authors write. Recognition of isolated Indigenous groups has almost halted under the Bolsonaro administration, another team of researchers has pointed out, and that recognition is crucial for conservation. "Mining companies file fewer requests on areas with known, uncontacted Indigenous peoples. This reinforces the importance of FUNAI's work on recognition and mapping of these groups," Villén-Pérez said.

Constitutional Rights

Yanomami, Munduruku, and Kayapó lands have been especially under pressure for decades, but threats have intensified under the Bolsonaro administration. As a presidential candidate in 2018, Bolsonaro himself promised "not to demarcate a single square centimeter more for Indigenous lands."

Anthropologist Fabio Ribeiro, coordinator of FUNAI's Ethno-environmental Protection Front Cuminapanema in northern Pará, warned that besides large mining companies pushing for more flexible environmental laws, there's "an epidemic of wildcat [illegal] mining operating all over the Amazon." In recent years, organized crime has taken special interest in these small mining operations, bringing further threat to the Amazon and its Indigenous Peoples. "In some places you can see wildcat mining just about 2 kilometers (about a mile) away from Indigenous villages," he said.

"In some places you can see wildcat mining just about 2 kilometers away from Indigenous villages."

On the other end of this tug-of-war is the Brazilian constitution, which recognizes Indigenous Peoples' rights to self-determination and the land they have traditionally occupied. The Brazilian state, according to article 231, must "demarcate [these lands], protect [them] and ensure respect for all of [Indigenous Peoples'] property."

The passing of PL 191/2020 could be a blow to these constitutional rights. Experts expressed concern about the bill not delimiting the area that can be assessed for survey and operation and possibly legalizing wildcat mining operations. Two communities from the Kayapó Indigenous group are particularly at risk, Villén-Pérez said. "Over 80% of the Xikrin do Rio Cateté land in Pará State is under mining requests," she explained, and the Baú Indigenous land, also in Pará, could have almost 80% of its territory used for mining activities if the bill is approved, according to the study.

Wildcat mining for cassiterite was documented in the Tenharim do Igarapé Preto Indigenous land in Amazonas State, Brazil, in 2018. Credit: Vinícius Mendonça/Ibama, CC BY-NC 2.0 (bit.ly/ccbync2-0)

Cascade of Negative Effects

Deforestation associated with the mining industry, said Ribeiro, would unleash a cascade of negative effects, especially on isolated Indigenous groups. "They are deeply integrated to their landscape and highly dependent on their land and could have scarcer access to natural resources due to deforestation and riverine contamination," Ribeiro said.

Increased contact with non-Indigenous people can also pose a serious health threat to isolated Indigenous groups, who are epidemiologically more vulnerable to certain viruses and other diseases carried by outsiders, Ribeiro added.

The use of mercury in mining also poses a problem, the authors say. Neurosurgeon Erik Jennings Simões, who has been the doctor to the Zo'é people in northern Pará since 2003, warned that widespread mercury exposure affects contacted and isolated Indigenous groups alike. A 2020 study from the Oswaldo Cruz Foundation and WWF Brazil showed that all Mundurukus, for instance, have some level of mercury contamination—six in 10 at unsafe levels (bit.ly/Mundurukus-mercury).

"[Mercury poisoning] is a silent, chronic, and sluggish contamination disguised by other symptoms."

"Mercury gets to Indigenous diets through contaminated fish, causing diffuse poisoning even to people living far from mining areas," Simões explained. Moreover, he said, mercury poisoning is difficult to track: "It's a silent, chronic, and sluggish contamination disguised by other symptoms: depression, irritability, trembling, and visual, memory, and concentration challenges, giving the false impression of noncontamination."

Simões said he recently got approval to set up a reference center to study chronic mercury exposure–related diseases in Pará. "[Brazil's] Special Secretariat of Indigenous Health, SESAI, reckons this is a problem, and they're trying to get experts together to come up with this reference center. This is an important step forward, despite all the backtracking," he said.

Financial Forces

According to journalist Maurício Angelo, founder of the watchdog group Mining Observatory, mining companies are not the only ones interested in the passing of PL 191/2020. International banks—stakeholders of these companies—are also part of the game.

An investigation by Mining Observatory last year showed that German banks invested more than $1 billion in mining companies involved in socioenvironmental conflicts in Brazil between 2016 and 2021 (bit.ly/banks-invest-mining). The British firm Anglo American, one of the world's largest mining companies, was the main beneficiary, having received $627 million from Commerzbank. International banks such as HSBC, BNP Paribas, Barclays, UBS, and Rabobank are also investors in companies such as Vale do Rio Doce, BHP Billiton, Glencore, and the Rio Tinto Group.

"Many of these banks are signatories of the United Nations' Principles for Responsible Banking and have their own internal sustainability agendas—and at the same time, they have vested interests in maintaining and expanding mining operations," Angelo said. "If the bill passes, mining requests that are already high can skyrocket, and wildcat miners will feel even more legitimized than they do now."

By **Meghie Rodrigues** (@meghier), Science Writer

Large Herbivores May Improve an Ecosystem's Carbon Persistence

Wildlife and open-canopy ecosystems like grasslands are rarely a part of discussions surrounding climate change mitigation. Now, a new review points to interactions between wild herbivores and vegetation to show how restoration efforts could be optimized by aligning climate goals with biodiversity conservation (bit.ly/large-herbivores).

The idea that herbivores are necessarily bad for carbon storage because they consume and disturb vegetation is "far too simplistic and risks poor land management decisions with bad consequences for biodiversity," said Jeppe A. Kristensen, the paper's lead author and a fellow at the School of Geography and the Environment, University of Oxford.

Terming grasslands as "overlooked global reservoirs of carbon," the research shows how herbivores redistribute carbon from aboveground vegetation (where it is vulnerable to disturbances like wildfire and disease) into more persistent belowground soil pools. Soil pools are composed primarily of undecomposed plant and animal residues (particulate organic matter) and more resistant carbon stabilized by interaction with mineral soil particles (mineral-associated organic matter).

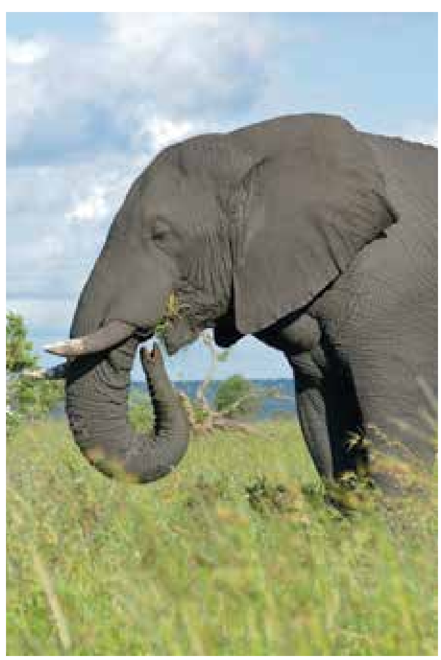
By grazing, Kristensen explained, herbivores recycle plant material to the soil via dung and urine. Decomposers in the earth (mostly microbes, but also larger animals like earthworms) feed on this nutrient-rich resource and bury fractions of it in the soil. By increasing the amount of carbon cycled through the soil, Kristensen and his coauthors argued, ecosystems with large herbivores may store a larger fraction of total ecosystem carbon in pools less vulnerable to perturbations than living plant biomass.

The paper presents a holistic framework of linkages between vegetation, large herbivores like elephants and wild boars, smaller organisms like earthworms and dung beetles, and microbes. Aboveground and belowground carbon sequestration services provided by these living elements of an ecosystem ought to be viewed as a whole rather than as a series of singular foci, the paper argues.

"There is a lot of focus on aboveground carbon. And nature management efforts are usually about increasing forest area. But soil carbon is an important aspect, and herbivores improve soil carbon and nitrogen sequestration," said Judith Sitters, a researcher in forest and landscape ecology at Wageningen University and Research who did not contribute to the new paper. Sitters was, however, the lead author of an earlier paper that showed how megaherbivores (animals weighing more than 1,000 kilograms) increased both carbon and nitrogen pools in the soil (bit.ly/megaherbivores-soil). Sitters added that megaherbivores like elephants and rhinos have a far greater impact on key ecosystem processes than smaller ones like zebras because of the amount of food they eat and the amount of dung they deposit.

An Ecosystem-Wide Perspective

For millions of years, herbivores have been integral to how ecosystems work. Sumanta Bagchi, an associate professor with the Centre for Ecological Sciences and the Divecha Centre for Climate Change at the Indian Institute of Science, said the presence of herbivores changes "the quality and quantity of food supply for microbes in soil." In the absence of herbivores, Bagchi said, "carbon's residence time in the soil is reduced."



Large herbivores, like this elephant in Kruger National Park in South Africa, may help grasslands serve as carbon sinks. Credit: Bernard DUPONT, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Bagchi was not involved in the new review but is one of the authors of an earlier paper suggesting why moderate levels of grazing could promote net soil carbon storage in ecosystems (bit.ly/grazing-carbon-storage).

The paper presents a holistic framework of linkages between vegetation, large herbivores like elephants and wild boars, smaller organisms like earthworms and dung beetles, and microbes.

Maintaining the influence of large herbivores on grazing ecosystems through conservation and rewilding efforts could be of "high importance" for soil carbon sequestration, Bagchi said.

Kristensen agreed, suggesting "a mix of climate-friendly forests, high-yielding agriculture, more extensive semipastoral systems, and dedicated nature parks where biodiversity is given first priority" as perhaps the best way to optimize multiple goals like climate change mitigation and biodiversity conservation.

Scientists like Bagchi, Sitters, and Kristensen are not alone in highlighting the links between biodiversity and climate change. In 2020, two bodies of the United Nations (the Intergovernmental Panel on Climate Change and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services) released a landmark report to highlight how "functional separation" between the fields of climate change and biodiversity "creates a risk of incompletely identifying, understanding and dealing with the connections between the two" (bit.ly/UN-report-2020).

By **Rishika Pardikar** (@rishpardikar), Science Writer

Lake Michigan's Salinity Is on the Rise

Lake Michigan is a major resource for drinking water, manufacturing processes, and other economic gains for the state of Michigan and surrounding areas. However, it's no secret that human activities have affected water quality in the Great Lakes, particularly in recent years. A recent study in *Limnology and Oceanography Letters* is now showing by just how much (bit.ly/lake-michigan-chloride).

Between the 1800s and 2020, chloride levels in Lake Michigan have risen from 1–2 to more than 15 milligrams per liter. And we can expect that rise to increase over the next 200 years, reaching 24 milligrams per liter, which will not only affect water quality but also harm nearby ecosystems.

Much of the spike has been caused by human activity, especially road deicing, according to Hilary Dugan, a limnologist from the University of Wisconsin–Madison and lead author of the new study. Road salt is about 60% chloride, and it takes about 5 million metric tons of road salt to raise Lake Michigan's salinity by 1 milligram per liter of solution; at current rates, that increase takes 2–3 years. Much of that, researchers posit, comes from more than 300 tributaries to Lake Michigan, which vary in size and shape.

"[It's] a warning signal to people who rely on these water resources," Dugan said. "They're valuable to us because they're freshwater, and if we destroy that resource, that's going to have catastrophic effects on the way of life for everyone who lives in this region."

Testing the Waters

In July 2018, Dugan and her team tested water from 235 of approximately 300 tributaries leading into the lake, analyzing each sample for chloride. To approximate chloride load, tributary chloride measurements were compared against discharge estimates for each sampling point using U.S. Geological Survey stream gauge data.

Chloride concentrations varied widely across tributaries, ranging from less than 1 to 265 milligrams per liter, indicating that many, but not all, tributary chloride concentration levels are below the Environmental Protection Agency's (EPA) 230 milligram per liter toxicity threshold. The highest concentrations were found in southern Wisconsin and Indiana, where five tributaries sampled—the Grand, St. Joseph, Fox, Kalamazoo, and Milwaukee rivers—accounted for 71% of the chloride increase. According to Dugan, greater population and industrial density (and thus more roadways and demand for wintertime deicing) and larger tributary size contributed to these inputs.

Using current data and a mass balance model, researchers also projected that over the next 2 centuries, Lake Michigan's chloride concentrations will rise from 15 to 24 milligrams per liter.

Even levels below EPA thresholds can be cause for concern, said Rick Relyea, a freshwater ecologist at Rensselaer Polytechnic Institute. "We don't really have tremendous

"I want the takeaway to be that we need to rethink how much salt we're using and how salt is regulated and monitored."

data to know what concentration is going to impact things," he said. Government regulations in the United States were set decades ago on the basis of limited data, yet Relyea, who was not involved in the new study, said recent research has shown that levels as low as 40 milligrams per liter can harm aquatic organisms like zooplankton. "This means we have time to turn this around before impacts are pervasive," he said.

Although road salt is the largest contributor to increases in salinity, Dugan said, it's not the only one. "Road salt is maybe half" of the chloride that winds up in waterways, she said. "The other half is livestock, fertilizer, water softeners." Still, she believes that more judicious and cost-effective use of road salt has the greatest potential to limit ecological damage caused by an increase in the Great Lakes' salinity.

"I want the takeaway to be that we need to rethink how much salt we're using and how salt is regulated and monitored," Dugan said. "I think we have an opportunity to use a lot less salt and still maintain public safety."

Relyea agreed, pointing out that lakes across the northern United States, Canada, and Europe all have seen salinity levels climb from 3–5 millgrams per liter 40 years ago to 15–20 milligrams per liter today. Like Dugan, Relyea said the study's findings add to a growing call to do something about the amount of salt humans add to the environment before there are drastic ecological effects.

By **Robin Donovan** (@RobinKD), Science Writer

Deicing of roads along the shores of Lake Michigan, seen here near Chicago, contributes to the increase in the lake's salinity levels that has been observed over the past 200 years. Credit: R Boed, CC BY 2.0 (bit.ly/ccby2-0)

An Ambitious Vision for the Future of Scientific Ocean Drilling

R/V JOIDES Resolution *departs from Lautoka, Fiji, in January 2020 at the start of International Ocean Discovery Program Expedition 378. Credit: Phil Christie and IODP*

The summer of 1966 was a watershed time in the geosciences. On 24 June of that year, as the formative ideas and observations of plate tectonic theory were continuing to gel in so many discussions and publications, the National Science Foundation (NSF) and the regents of the University of California signed the momentous contract establishing the first phase of the Deep Sea Drilling Project (DSDP).

The purpose of DSDP was scientific exploration through the collection of seafloor core samples from around the world. These cores would help researchers explore for natural resources, study seafloor compositions and ages, and otherwise inform a variety of questions about Earth's deep-ocean environs. Just over 2 years later, in July 1968, a team of distinguished scientists sailed from Orange, Texas, aboard the drilling vessel *Glomar Challenger*, bound for sample sites in the Gulf of Mexico and the western Atlantic Ocean. This was DSDP Leg 1. Soon after, DSDP Leg 3 retrieved samples that provided definitive proof that new seafloor is created at rift zones, further supporting the theory of plate tectonics.

Over 55 years later, more than 275 expeditions have been completed through DSDP and its successors—the Ocean Drilling Program, the Integrated Ocean Drilling Program, and the International Ocean Discovery Program (IODP). These explorations have yielded staggering returns, enabling pure discovery and revealing foundational knowledge about the geosphere, the biosphere, and the entire Earth system. The ocean drilling programs also have yielded economic returns. For example, through the discovery of salt domes linked to oil and gas resources, expanded

More than 275 expeditions have been completed through the Deep Sea Drilling Project and its successors, yielding staggering returns.

knowledge of the deep biosphere led to technological advances in piston coring and provided countless opportunities for training and education in science and engineering for the next generation of explorers.

These gains not only have validated the visionary and long-term investments in the

programs but also have been vital to our understanding of planetary health and sustainability. For example, continued advances in drilling, analysis, and recovery of cores have increased the temporal and spatial resolution of paleoclimate and paleoceanographic records needed to improve global climate forecasts.

Expanding support for scientific ocean drilling is integral to ensuring the long-term health of science, technology, engineering, and mathematics (STEM) research in the United States. It is also integral to strengthening the role of STEM in building a more sustainable and inclusive future on Earth and perhaps even in gaining insights into the geology, form, and function of other worlds.

Scientific ocean drilling will continue to be the foundation upon which advances in climate science, risk assessment, and resilience planning are built.

A Framework for the Future

In 2018 and 2019, an international community of Earth scientists came together to produce a visionary planning effort for scientific ocean drilling. This effort underscored the vast potential for scientific and societal return on investment of expanded support for such drilling and resulted in IODP's 2050 Science Framework, titled "Exploring Earth by Scientific Ocean Drilling." This consensus framework was crafted with the grassroots input of scientists from 23 nations and was initiated through six major international workshops conducted by the scientific ocean drilling communities in Australia and New Zealand, China, Europe, India, Japan, and the United States. The workshops engaged more than 650 scientists, with substantial representation by women (30%) and early-career scholars (40%).

"Exploring Earth" charts an ambitious path forward, laying out strategic objectives that focus on major challenges within the Earth sciences. These challenges include improving our understanding of the limits of habitability for life on Earth, many aspects of Earth's climate system (including feedbacks and tipping points related to sea level rise and ice sheet stability during times when atmospheric carbon dioxide concentrations were higher), the life cycle of tectonic plates, global cycles in energy and matter during seafloor spreading, and geophysical hazards like earthquakes and tsunamis that affect society.

Five flagship initiatives detailed in the framework provide an integrated road map to address the strategic objectives and societally critical issues by obtaining the necessary core samples and crustal records. For example, the "Probing the Deep Earth" initiative will improve our understanding of Earth's formation and the inextricable connections among tectonics, climate, and planetary habitability. And the "Diagnosing Ocean Health" initiative will build on our understanding of how past catastrophic events have affected biology to refine assessments of how rapidly ocean health may deteriorate in response to climate change. Drilling into Earth's crust, recovering cores, and installing seafloor observatories are the only ways to accomplish these ambitious initiatives.

At the heart of "Exploring Earth" is a set of "enabling elements" that center enhancements in diversity and research community-led planning. These efforts focus on addressing the well-known challenges regarding equity and diversity in the geosciences by promoting recruitment of diverse science parties, codifying enhancement of diversity and inclusion in expedition objectives and as enduring principles in future scientific ocean drilling programs, and using telepresence technology to conduct ship-to-shore video conferences with minority-serving institutions. This collaborative and active engagement is intended to foster mentorship and a sense of belonging for current and future explorers in ocean drilling and exploration environments.

Inspired by the vast international effort to create "Exploring Earth," leaders from many U.S. oceanographic research and education institutions (represented by the contributing authors acknowledged below) have come together to express their strongest support for continuing to fund scientific ocean drilling. This impressive framework should serve as a valuable model for similar community-led planning efforts, and implementing the vision laid out in "Exploring Earth" will affect the entire Earth sciences community. Below I highlight some of the wide-ranging strategic considerations and science drivers that provide a compelling rationale for continuing this support as part of the nation's commitment to renewed and enhanced investment in infrastructure and communities.

Maintaining Our Leadership

The decision by the United States to rejoin the Paris Agreement is an opportunity to highlight the country's leadership in ocean and climate science. Much of our knowledge of past climate and sea level change has derived from studies of ocean sediments collected via ocean drilling. Observations from these studies have, for decades, provided ground truthing of climate models, including those considered by the Intergovernmental Panel on Climate Change in its reports, and been key to our understanding of future climate risks and assessment of possible adaptation and remediation options. Scientific ocean drilling will continue to be the foundation upon which advances in climate science, risk assessment, and resilience planning are built, as interdisciplinary research expeditions and analyses address key questions about Earth's past, present, and future.

Another example of the acute societal relevance of drilling efforts relates to studying the tectonic processes that result in megathrust earthquakes and tsunamis, which cause some of our planet's deadliest and costliest natural disasters, especially among highly vulnerable communities. Scientific ocean drilling has provided, and will continue to provide, crucial insights and state-of-the-art monitoring data to enable increasingly reliable forecasts and assessments of risks to vulnerable populations and infrastructure. These data may, for example, further inform our knowledge of fault locations and conditions that lead to destructive events along highly populated coastal areas surrounding the Pacific Ocean.

Continued leadership in ocean and climate science requires enhanced investment in the scientific drilling community and its associated infrastructure, which is an essential complement to other ocean-observing and satellite platforms. In particular, investment is needed for a new global-class drilling vessel. The strategic long-term value of such bold investments has multiple dimensions. Modern ocean and climate observations require the context of the geologic record to identify real signals and trends amid variability in background conditions and to discern natural versus anthropogenic change. Furthermore, vast areas of our oceans remain unexplored or underexplored—we have mapped more of the Moon's surface than of

Earth's seafloor, and we know little about the sizes of deep-ocean and lithospheric carbon reservoirs. These reservoirs, which could contribute considerably to climate change, require substantial additional exploration and sampling to assess climate mitigation strategies accurately.

Research, education, and public engagement activities supported by scientific ocean drilling expeditions, currently through IODP, have created a legacy of effective STEM leadership and workforce development. IODP and predecessor programs have enabled numerous scientists not just to carry out cutting-edge research but also to serve as educators and mentors to thousands of students around the world, thus repeatedly fostering future generations of leaders and innovators. Building and maintaining a sustainable future requires a society in which people understand and trust science. Thus, we need programs that consistently produce trustworthy and societally relevant research and that provide STEM training to numerous scientists and science educators so they can seek out and convey knowledge about our planet to the public and to decisionmakers.

The International Ocean Discovery Program and predecessor programs have enabled numerous scientists not just to carry out cutting-edge research but also to serve as educators and mentors to thousands of students around the world.

The past 55 years of international scientific ocean drilling collectively represent one of our nation's most successful and significant investments in advancing basic research about Earth, as well as in advancing STEM education, the economy, and workforce development. It is no coincidence that so many leaders in the Earth and planetary sciences today, at home and abroad, cut their teeth in research by participating in the drilling programs. Simply put, these programs build talented scientists and educators. No doubt the next generation of leaders and innovators who will help the United States and the international community tackle challenges—from climate change to natural hazards—includes many who have already been involved in scientific ocean drilling.

Acknowledgments

In addition to the author's perspectives, this article reflects the contributions and views of Peter de Menocal, Tom Frazer, Lisa Graumlich, Margaret Leinen, Roberta Marinelli, Claudia Mora, Bradley Moran, Christina Ravelo, Maureen Raymo, Demian Saffer, Brian Taylor, and Debbie Thomas. We express our deepest gratitude to NSF for its multidecadal commitment to scientific ocean drilling.

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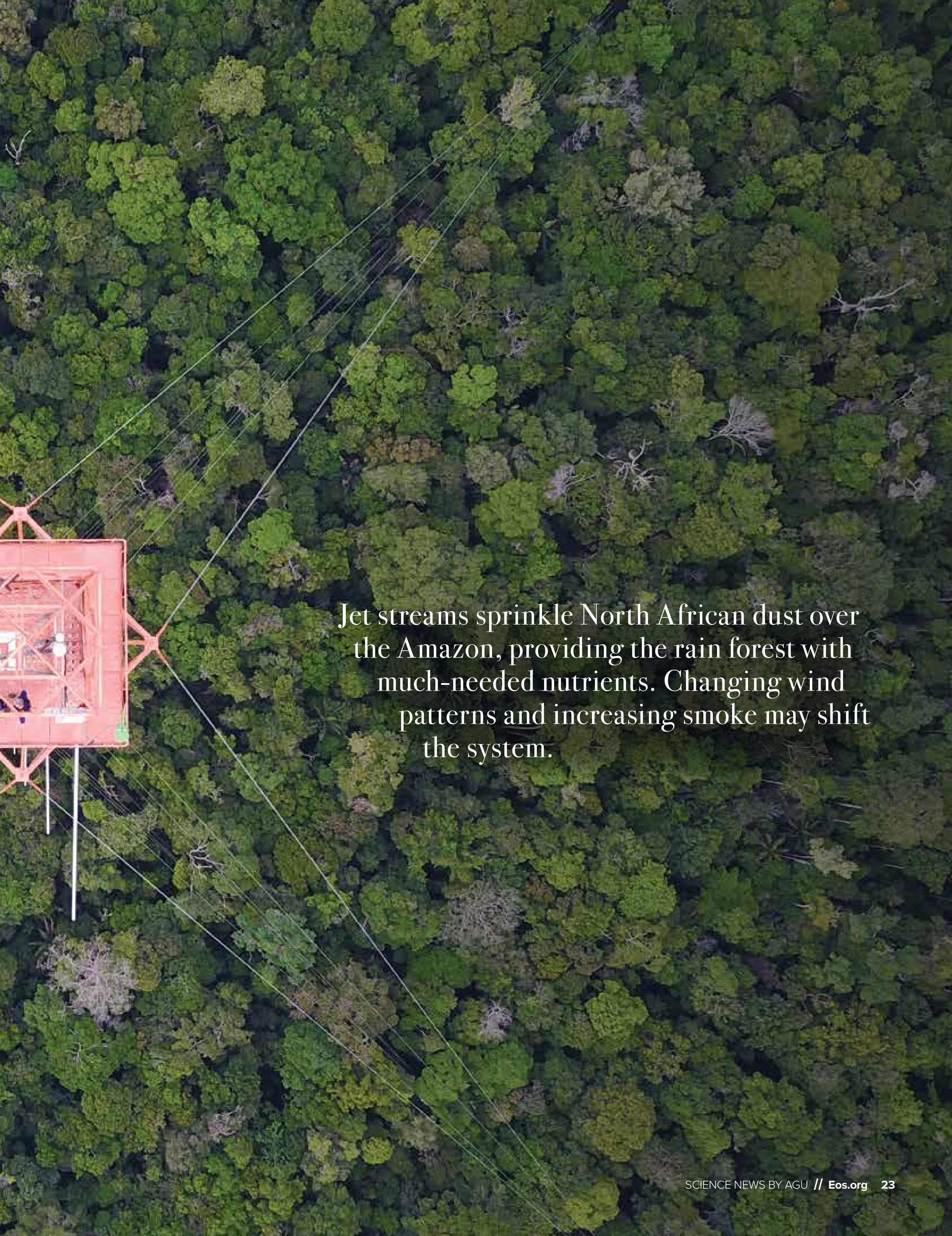
▶ **Read the article at bit.ly/Eos-ocean-drilling**

AFRICA'S EARTH, WIND, AND FIRE KEEP THE AMAZON GREEN

BY J. BESL

The Amazon Tall Tower Observatory is a joint Brazilian-German research station with a 325-meter tower making environmental observations in the Amazon. Credit: Achim Edtbauer/MPI-C



Jet streams sprinkle North African dust over the Amazon, providing the rain forest with much-needed nutrients. Changing wind patterns and increasing smoke may shift the system.

The Amazon Tall Tower Observatory (ATTO) is exactly what it sounds like: a very tall tower, dotted with sensors, jutting above the canopy of the largest rain forest on Earth. To reach the site, researchers drive several hours north from Manaus (the capital of Brazil's state of Amazonas), then turn down a dirt road. Hours later, they clamber into a boat and head down the Uatumã River to reach another muddy road taking them deeper into the jungle. At the end sits ATTO, the tallest structure in South America, an orange-and-white spire 1 meter higher than the Eiffel Tower.

Why do researchers make the trek? For many, it's to study dust—not the fluffy stuff that collects under furniture, but the lightweight minerals swept up from the Sahara desert more than 5,000 kilometers away in North Africa. Each grain of dust carries key nutrients like phosphorus and iron, and if the winds are right, those grains help fertilize the Amazon basin. The same material that gives the Sahara its dull beige tone in satellite images is the reason the Amazon stays so brilliantly green.

The phenomenon relies on two conditions: extremely dry soils and very strong winds. Research indicates that these reliable conditions may change: Models show that North Africa is destined to get wetter, and a warming climate will shift existing wind patterns. Fires are also expected to change, further complicating the outlook for dust transport.

Nutrients in tiny specks of dust may sound like minor contributions to the massive, complex ecosystems of the Amazon, but their effects are major.

"Dust," said Cassandra Gaston, an atmospheric chemist at the University of Miami, "has always been a big player in the climate system."

"DUST HAS ALWAYS BEEN A BIG PLAYER IN THE CLIMATE SYSTEM."

Aerosols at Altitude

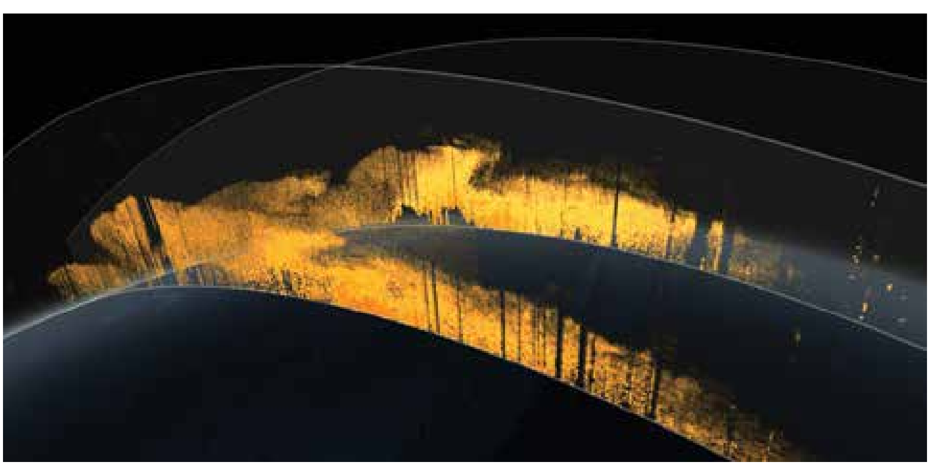
Dust falls into the category of aerosols, small particles suspended in air. Individually, aerosols are rarely wider than a human hair. Collectively, aerosol clouds (including clouds of smoke) can alter weather patterns and be visible from space.

In 2006, NASA launched a specific mission to focus on aerosols. Called CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation), the satellite records aerosols in three dimensions and maps the movement of aerosol clouds. Although ground research sites like ATTO can study aerosol chemistry at a specific spot, CALIPSO provides an overhead understanding of aerosol (including dust) transport.

"Satellites can provide routine sampling on a global scale," said Hongbin Yu, a research physical scientist with the Climate and Radiation Laboratory at NASA Goddard Space Flight Center in Greenbelt, Md. With a global perspective, scientists can see where the world's dust originates. It's commonly thought that Africa contributes more than half of global dust to the atmosphere, he said.

With the benefit of spatial and temporal coverage, the satellite also helps NASA pinpoint the total mass of African dust leaving the continent. Using lidar, CALIPSO builds vertical dust maps depicting slices of Earth's atmosphere; each map looks like a grimy window showing the concentration of African dust at different altitudes.

Stronger winds send dust higher in the atmosphere, which can affect climate. Dust scattered in the upper atmosphere will absorb sunlight and create an elevated heat source, explained Yan Yu, an assistant professor in the Department of Atmospheric and Oceanic Sciences at Peking University. If there's enough dust in the upper atmosphere, it can reduce the usual temperature gradient that affects wind patterns and precipitation, she said.



NASA's CALIPSO satellite uses lidar to generate dust maps, which can show the concentration of dust at different altitudes. Credit: Scientific Visualization Studio, NASA

Points of Origin

Even with satellites, researchers still aren't sure exactly where in the vast Sahara the dust is coming from. "It's very hard to keep track of these dust particles as they're being blown across the desert," Gaston noted. The source matters, though, because nutrient concentrations may change from place to place.

Originally, researchers hypothesized that the Bodélé Depression, a massive former lake bed in Chad, was the main source of dust delivered to the Amazon. "That is very natural thinking, because the Bodélé Depression is the leading source [of dust emissions] globally," explained Yan Yu. The depression is located between two mountain ranges, which generate strong southwestward winds. But those winds also send dust directly into the Intertropical Convergence Zone (ITCZ), a seasonal rain belt. Rainstorms can knock dust from its delicate trajectory across the Atlantic.

A second likely source is El Djouf, a desert straddling the border between Mauritania and Mali. The site is geographically closer to the Amazon, making El Djouf dust more likely to survive in the atmosphere en route, explained Yan Yu.

At 325 meters, the Amazon Tall Tower Observatory stands 1 meter higher than the Eiffel Tower and is the tallest structure in South America. Credit: Jsaturno/Wikimedia, CC BY-SA 4.0 (bit.ly/ccbysa4-0)

Aerial view of the Amazon rain forest near Manaus, the closest urban center to the Amazon Tall Tower Observatory. Credit: Neil Palmer/CIAT, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Regardless of the source, no specific location in Africa actually contributes all that much dust to the Amazon. That's because once suspended, dust particles behave like little paratroopers slowly sinking back to Earth. Most of the dust lands in the Atlantic Ocean, where its iron nutrients fuel the growth of plankton and support marine food webs. Only dust particles reaching high altitudes over Africa have the potential to reach the Amazon.

In 2015, NASA reported that trade winds carry 165 million metric tons of dust up and away from northern Africa each year. Only an estimated 25.1 million metric tons end up in the Amazon basin. "Really, a small fraction of dust can reach the Amazon," said Hongbin Yu.

Every particle that reaches the basin delivers a crucial jolt of nutrients, though. NASA estimates that roughly 21,770 metric tons of phosphorus from Africa arrive in the Amazon each year, spurring growth in a region where 90% of soils are depleted of phosphorus, a key element for energy transfer in plants.

Three-Station Welcoming Committee

After its journey over the Atlantic Ocean, the arriving dust is welcomed to the Americas by a trio of prominent research stations. In the Caribbean, the University of Miami's Barbados Atmospheric Chemistry Observatory has collected data since 1966. ATTO, a Brazilian-German partnership, gathers aerosol information from the heart of the Amazon. A newer site in Cayenne, French Guiana, called ATMO Guyane, monitors air quality from the edge of the rain forest; the local health department collects air quality data and shares its filters and findings with researchers.

"It's really nice to have the three research stations, because they're all impacted by African dust in different ways," said Anne Barkley, a Ph.D. student at the University of Miami.

Barkley's research centers on data from ATMO Guyane and shows that a significant portion of phosphorus arriving in the Amazon comes from African dust. The ITCZ's consistent delivery system allows the Amazon to be more productive than it otherwise would be, she noted.

In the highly productive Amazon, most of the resident phosphorus is locked away in living trees and other plants. The phosphorus will return to the soil only when the plant decays. However, it may not stay there long, thanks to the forest's namesake rain. "Soil nutrition gets washed out frequently in the Amazon," explained Yan Yu.

The phosphorus recycled during plant decay is "orders of magnitude more important" than African dust to the Amazon, noted Barkley, but findings from ATTO and ATMO Guyane show that African dust still plays an important role in the rain forest. Comparing observations among the three stations allows researchers to determine what's arriving, where it's coming from, and how the transport process is changing.

Earth, Wind, and Fire

Wetter conditions in the Sahara may reduce the amount of dust ready for transport. More rain can produce more vegetation in the region, and "any increase in vegetation will decrease the amount of dust trans-

ported," explained Barkley. In fact, a wet year in the Sahara can reduce the amount of available dust by up to an estimated 29%.

The central Sahara has slowly grown greener over the past 15 years. Increasing temperatures associated with climate change have led to stronger evaporation patterns, and the resulting condensation rains down onto dry land. The trend is likely to continue: "The latest IPCC [Intergovernmental Panel on Climate Change] report has higher confidence that there will be an increase in rain over the Saharan desert," said Barkley.

Just as climate change brings wetter conditions to dusty North Africa, it will also likely contribute to increased numbers of forest fires throughout the rest of the continent. Such fires introduce another key aerosol for the Amazon: smoke.

Like dust, smoke carries crucial nutrients across the Atlantic. But because of their relative buoyancy and smaller size, smoke aerosols typically travel farther into the Amazon interior.

There are geochemical differences between dust and smoke as well. Because dust has more mass, it holds more nutrients. But not all nutrients are created equal. The phosphorus in dust is generally held in the mineral apatite, which doesn't readily dissolve. When dust reaches the Amazon, only an estimated 5% of its phosphorus is immediately available for plants to absorb, explained Barkley. Phosphorus in smoke, on the other hand, is more than twice as soluble; like a car at a junkyard being dismantled, the component parts of smoke are more easily separated and shared.

"Even though smoke has fewer nutrients, it tends to have a higher impact because it's immediately accessible to plants," said Gaston.

Regular rainstorms can wash the Amazon's nutrients from the soil and into the river. Dust from Africa resupplies the system. Credit: Neil Palmer/CIAT, CC BY-SA 2.0 (bit.ly/ccbysa2-0)

Smoke Is Always in Season

Research at ATTO shows that the arrival of dust and smoke varies seasonally. "It's not constant, but it comes in plumes, in pulses," explained Bruna Holanda, a postdoctoral researcher at the Max Planck Institute for Chemistry, which co-manages ATTO.

ATTO's sensors record the highest mass concentration of aerosols arriving in the central Amazon (around ATTO) from December to March, the rainy season, but the highest number concentration arrives between August and November, during the dry season.

That discrepancy indicates that dust, which has more mass, arrives primarily during the wet season when the ITCZ is aimed at the Amazon. According to Holanda's research, 90% of smoke reaching ATTO in the wet season comes from the burning of African biomass. (On average, Africa accounts for 70% of the burned land area on Earth.) Even in the dry season, when Amazonian fires are more likely to occur, 60% of smoke at ATTO still comes from Africa. Black carbon—the soot of burned plants—peaks at ATTO during this period.

It's important to note that the Amazon itself contributes smoke to the region, researchers say. Burns are a common method of deforestation along the rain forest perimeter. ATTO can differentiate between local and long-range aerosols, however, and researchers found that both smoke and dust coming from Africa are more chemically diverse than their Amazonian equivalents.

Regardless of origin, an increase in smoke is concerning to researchers. "Smoke makes it harder for water vapor and aerosols to combine and form clouds," said Holanda. That can delay precipitation, one of the defining characteristics of the Amazon rain forest.

"Deforestation doesn't just change the environment where you lose the vegetation," Holanda said. It causes "changes all across the atmosphere."

"DEFORESTATION DOESN'T JUST CHANGE THE ENVIRONMENT WHERE YOU LOSE THE VEGETATION." IT CAUSES "CHANGES ALL ACROSS THE ATMOSPHERE."

Dust in the Wind

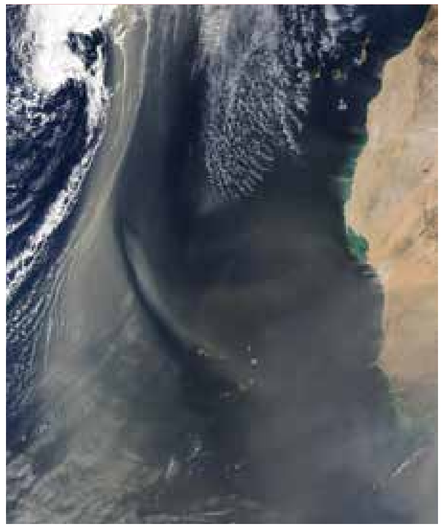
In addition to influencing the increase in smoke and reduction in dust, climate

change will also affect the other half of the aerosol transport equation: wind. Changing temperatures are expected to shift wind patterns, which could reroute the whole transatlantic transport process.

Dust can reach the Amazon only with help from a group of interlocking atmospheric systems. First, high winds must pry dust loose from the soil, then shoot it skyward on an atmospheric elevator. The African easterly jet, which cruises several kilometers above North Africa, is the first leg of the intercontinental journey. The jet is influenced by the temperature difference between the hot desert interior and the cooler coast along the Gulf of Guinea.

"A stronger temperature gradient usually results in intensified African easterly jets," explained Bing Pu, an assistant professor of geography and atmospheric sciences at the University of Kansas. High temperatures over North Africa can contribute to an anomalously strong jet. The so-called Godzilla dust storm of 2020, for example, delivered enough dust—nearly 22 million metric tons—to slash visibility in the Caribbean and trigger air quality warnings as far inland as Oklahoma. The African easterly jet is expected to continue to intensify as the interior of Africa warms relative to the coast, Pu said. "It all favors this westward transport."

The next step on the journey is the ITCZ, which acts as the Amazon's streaming service. The jet stream, which flows just north of the equator, connects Africa and South America. It also wobbles with seasonal weather. When the Northern Hemisphere is warmer, from June through August, the ITCZ pushes north and peppers African dust over the Caribbean. When the Southern Hemisphere is warmer, from December to March, the ITCZ shifts back south and sprinkles Saharan dust over the Amazon instead.



Aerosols are rarely wider than a human hair, but a large enough concentration can be viewed from space, as seen in this image of Northwest Africa from 3 February 2004. Credit: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC

The ITCZ is also determined by temperature gradients between the hemispheres. "We find that the difference between Northern Hemisphere and Southern Hemisphere surface temperature has a large impact on dust activities," Hongbin Yu said. Climate change will likely alter that balance and possibly throttle the strength of the ITCZ.

> "DUST IS CONTROLLED BY NATURE. IT'S CONTROLLED BY WIND AND BY RAINFALL AND SOIL MOISTURE. THAT'S WHY I BELIEVE DUST WILL BECOME MORE AND MORE IMPORTANT IN THE FUTURE."

History of the Holocene

Of course, wind patterns have shifted in the past. Marine sediment cores collected from both sides of the Atlantic demonstrate that the flow of dust is cyclic, with repeated intervals of lower dust deposition. Data from the western edge of the Amazon show that African dust has historically played little role in fertilizing areas farthest from the coast.

Juliana de Sousa Nogueira is a researcher at the Laboratory of Radioecology and Global Changes at Rio de Janeiro State University. (Nogueira is also a researcher at the Department of Forest Ecology at the Czech University of Life Sciences in Prague.) She and her colleagues explored the role of African dust transport in the western Amazon. The researchers took cores from Lake Pata in Brazil, an elevated lake in a relatively pristine pocket of the western Amazon, to look for "the DNA of the dust," she explained. Back in the lab, they examined isotopes, which "act like a fingerprint for the source," and backtracked wind trajectories to find likely locations. At Lake Pata, dust from the Andes and even from South Africa appeared to be stronger contributors in the western Amazon during the middle to late Holocene, indicating the role of sources in the Southern Hemisphere.

However, their findings show that since the African Humid Period ended roughly 5,500 years ago, the Saharan dust flux has increased fivefold in the western Amazon. African dust has played an increased role throughout the entire Amazon during the Holocene, said Nogueira, although the eastern regions closest to Africa still see the most benefit. "We can't take into consideration the Amazon as one thing," she said. "We have to understand dynamics in different parts of the Amazon."

Historically, periods of low dust deposition correspond to times when the ITCZ was at its weakest, too slow to scoop up massive amounts of desert dust. However, those intervals are also times when Africa was wetter, like during the African Humid Period. Researchers are unsure whether the lower dust records in sediment cores are a result of a wetter Sahara, a weaker ITCZ, or both. According to current models, however, both systems are predicted to shift back in the direction of generating less dust.

These variations make paleoclimate studies essential if researchers want to understand the evolution of the Amazon, said Nogueira. "The present is really clear because we have satellites, so we have 40 years of history. Forty years is nothing" in context, she said. "We have to always have a broader vision."

Dust from Africa adds phosphorus and other nutrients to the Amazon ecosystem, allowing the rain forest to stay productive even as rainfall washes nutrients downriver. Credit: Jay/Wikimedia, CC BY 2.0 (bit.ly/ccby2-0)

Complicated Next Steps

The current uncertainties about dust and smoke transport to the Amazon stem from a lack of data on both sides of the ocean. ATTO's first observations were in 2010, for example. There's a lack of comparative measurements coming from the North African desert, added Gaston. That presents future opportunities.

"We welcome collaboration with anyone interested in this research," said Gaston. "We'd love to work with more people to get a broader sense of what's happening."

Dust connects geology, chemistry, and atmospheric science. "It's all very interconnected," Barkley said of the research. When smoke is part of the conversation—incorporating arenas like politics, public health, and land management—"it gets really interesting, really fast," she said.

The issue of aerosol transport is also really complex; dust and smoke have positive effects and negative consequences, depending on whom, what, and where a study focuses. In Africa, for instance, fires are burning the savanna and diminishing air quality. In South America, smoke is helping fuel an ecosystem that can sequester carbon from the atmosphere. The air-clouding carbon and growth-stoking phosphorus are coming from the same fires.

Likewise, climate change will alter the dust transport system in different ways. A wetter desert and weaker jet stream may reduce dust transport, but a hotter climate will increase smoke transport. "The net balance of what gets transported to the Amazon is still definitely up for debate," Gaston said.

"We have so many tools, but we need synthetic analysis," added Yan Yu, ticking off the fields of geochemical analysis, Earth systems modeling, and satellite observations. "We really need to combine all these together to give us the complete picture of dust emissions and dust transport. This is really an Earth system problem. It's not a single climate or a single ecosystem," she said.

In addition, as the world reduces its air pollution emissions, Hongbin Yu said, atmospheric dust and smoke may become more relevant to the public. Industrial aerosols like sulfate and organic carbon are declining, thanks to a global effort to reduce air pollution, and that means aerosols like dust and smoke are more likely to cause future air quality issues. The public may think more about dust if events like the 2020 Godzilla storm start increasing in frequency. But unlike air pollution, there's not much one can do to corral dust.

"Dust is controlled by nature. It's controlled by wind and by rainfall and soil moisture," Hongbin Yu said. "That's why I believe dust will become more and more important in the future."

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▶Read the article at bit.ly/Eos-green-Amazon

THE NUTRIENT-RICH LEGACY IN THE AMAZON'S DARK EARTHS

By Kate Evans


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Fertile terra preta soils were created through centuries of carefully managed land use. Scientists are taking cues from these soils to better sequester carbon and improve soil for agriculture.

Across the vast Amazon basin, scattered patches of black and chocolate-brown earth stand in sharp contrast to the acidic, nutrient-poor red or yellow soils found in the rest of the rain forest. The dark soils are extraordinarily fertile, and the plant communities that grow there are different from those in the surrounding forest—higher in biomass, with a greater proportion of edible species like Brazil nuts and acai palms. Very often, they contain artifacts like ceramics or fragments of stone tools.

These soils are called terra preta, Amazonian dark earths (ADEs), or simply dark earths because they have been identified in Africa, Australia, Europe, and elsewhere outside Amazonia. They are also called anthrosols because almost all researchers agree that they were created by people. Dark earths have been found at hundreds of archaeological sites across the Amazon basin, covering an estimated 6,000–18,000 square kilometers. One study

used modeling to predict that terra preta soils might actually cover more than 150,000 square kilometers, or 3.2% of the total forest (bit.ly/Amazonia-soils).

Before Europeans arrived in the Americas—bringing conflict, exploitation, and infectious diseases that killed upward of 90% of the population—Amazonia teemed

TERRA PRETA SOILS MIGHT COVER MORE THAN 150,000 SQUARE KILOMETERS, OR 3.2% OF THE TOTAL AMAZON RAIN FOREST.

with human life. Archaeologists are still debating how many people lived there before the European conquest, but several estimates suggest they numbered between 6 million and 10 million.

Indigenous Amazonians made their homes on bluffs overlooking the rivers, where they fished and hunted and gathered and gardened. They domesticated plants, including manioc, sweet potato, and cacao. They carried out extensive earthworks, made roads, and modified wetlands. They set low-intensity fires to manage the landscape. And like humans everywhere, they produced garbage: fishbones, shells, manioc peelings, manure, weeds and crop residues, pottery, and charcoal.

Over generations, they turned that trash into treasure, creating rich, fertile earth good for growing crops. At the same time, the process sequestered large amounts of carbon in the soil. Scientists from a wide range of disciplines are now digging into terra preta for answers—not just for the new story it tells about Amazonia's past but also for the lessons, possibilities, and warnings it might hold for Earth's future.

Helping Plants "Grow Happy"

In the past, nonhuman explanations for the formation of terra preta have been suggested: sedimentation from floods, organic matter building up in lakes and small ponds, and ash fallout from Andean volcanoes.

In 2021, even, U.S. and Brazilian researchers published a paper proposing that the high fertility of Amazonian dark earths was the result of nutrients being deposited by rivers (bit.ly/amazonian-dark-earth). Pre-Columbian peoples then identified these areas of increased fertility and settled there, the authors argue. "Indigenous peoples harnessed natural processes of landscape formation," they write, "but were not responsible for their genesis."

Most archaeologists, soil scientists, geographers, and anthropologists working in the Amazon, however, say there is little doubt that dark earths were made by humans. The prevailing winds blow the wrong way for volcanoes to be involved. Enriched soils are frequently found on top of bluffs—locations very unlikely to flood or collect water but wonderful places for people to live. Flooding can't explain the wide variety of landscape types in which dark earths are found, why they are usually riddled with pottery fragments, or the fact that excavations most often reveal them within or around human-made mounds, pits, paths, and ditches.

The precise origins of terra preta remain unclear, but the lives of contemporary Indigenous Peoples in today's Amazon give some insight into how these dark earths might have been made. Archaeologist Morgan Schmidt, a research affiliate at the Massachusetts Institute of Technology (MIT), has spent years researching the soils in partnership with the Kuikuro people of the upper Xingu River in Brazil's state of Mato Grosso, whose ancestors have lived there for centuries.

To this day, Kuikuro farmers purposefully create dark earth for crop cultivation—they call it *eegepe*—and the composition of the soil and its spatial patterns are similar to those found around archaeological sites. The Kuikuro throw food and fire waste into trash middens around their houses, Schmidt said, and after a few years, plant crops and fruit trees on top.

"They're constantly managing these plants and these crops in the backyard and improving the soil all the time," Schmidt said. "They're really proud of being able to make that fertile soil so that the plants can 'grow happy,' as they say." Those modified soils end up rich in phosphorus, nitrogen, calcium, and carbon, with a pH much higher than other Amazonian soils.

One Indigenous colleague, Kanu Kuikuro, described the recipe to Schmidt: "Charcoal and ash we sweep, gather it up and then throw it where we will plant, to turn into beautiful eegepe. There we can plant sweet potatoes. When you plant where there is no eegepe, the soil is weak. That is why we throw the ash, manioc peelings, and manioc pulp."

The Kuikuro also travel to nearby archaeological sites to grow crops in the older dark earths there. These days, they go by motorbike. Their contemporary middens now contain the odd battery and chunk of plastic. But in general, Schmidt thinks that the Kuikuro farmers are creating dark earth in much the same way their pre-Columbian ancestors did—the ancients just did it on a much bigger scale because there were so many more of them. But were they also making it deliberately, to improve the soil?

"There's no way we can ever know what people were thinking in the past," Schmidt said. "It's very hard to find evidence of intentionality. But the Kuikuro people that we work with have demonstrated continuity in the area, and we find the same pattern of soil enrichment in the modern village and in the prehistoric sites, so we can be reasonably sure they were doing the same things in the past."

Fertile Soils, Drought-Prone Forests

When the inhabitants of humid tropical areas are gone, most signs of human occupation are rendered invisible after 500 years. Wooden homes and ceremonial buildings rot away. Roads become overgrown. Mounds, ditches, and other earthworks are blurred by the vegetation, becoming visible only when the forest is clear-cut.

But below the surface, ceramic-strewn dark earth remains a tangible sign of human occupation. Finding out how much of it

there is should shed light on the extent to which humans modified the rain forest, as well as how much carbon is locked away.

Mapping the extent of terra preta has been difficult, given the immense size of Amazonia, the remoteness of parts of it, and the thick forest canopy. (Many archaeological sites have, in fact, been revealed by Brazil's accelerating deforestation.) Recent research, however, suggests that the shadow of dark earths can be seen from space.

Paleoecologist Crystal McMichael from the University of Amsterdam and her coauthors used satellite imagery to identify spectral signatures—differences in how light is reflected in forests growing on dark earth and those on other Amazon soils.

They proved that remote sensing can capture past forest disturbances and identify terra preta, but what they found surprised them. McMichael expected that fertile dark earths would support lush, green trees that were resistant to drought. The results showed the opposite: Forests growing on anthropogenic soil actually had less green canopy with lower water content compared with other soils, and these differences were accentuated in dry years, making the dark earth forests more fire prone and susceptible to drought.

There are several possible explanations for this discrepancy, McMichael said. Other studies have found that dark earths tend to support different kinds of trees, including a higher proportion of edible palm species, implying that pre-Columbian peoples changed the structure of the forest. Perhaps those areas of forest are still recovering from periodic controlled burns and clearing—500 years is only a couple of tree generations, after all.

Or it could be that these rich soils have continued to attract farmers for centuries, McMichael said. "The legacy of using them continues even today, and I think that's part of why there are no giant lush things, and there are these shorter-stature palm-rich forests there."

A worker turns soil containing biochar in a corn field at the Villa Carmen Biological Station in Pilcopata, Cusco. Locals farming in areas of the Peruvian rainforest commonly burn fields to improve soil quality. Credit: Enrique Castro-Mendivil/Alamy Stock Photo

"Guardians of This Ancient Footprint"

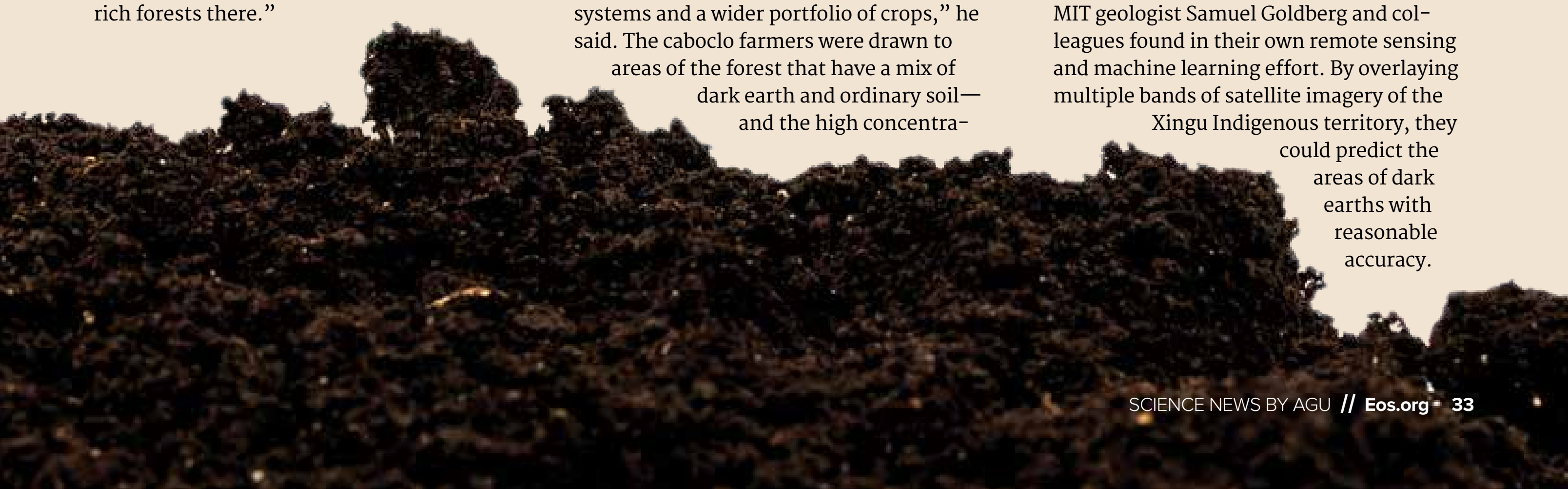
It's true that traditional farmers value dark earths, said ethnoecologist André Junqueira from Wageningen University in the Netherlands, but the relationship is not quite as simple as he expected when he began his research. Junqueira has studied how caboclos—present-day Amazonian peoples of mixed descent—cultivate the landscapes along Brazil's Madeira River. The caboclos appreciate the high fertility of terra preta and plant some of their more nutrient-demanding crops and varieties there. But weeds, as well as cultivated crops, grow like wildfire in dark earth, Junqueira said, "so they actually require much more work to be maintained."

"From a farmer's perspective, what people like most is to have different types of soil that can sustain multiple cultivation systems and a wider portfolio of crops," he said. The caboclo farmers were drawn to areas of the forest that have a mix of dark earth and ordinary soil—and the high concentration of useful trees and palms found near archaeological sites was a bonus, too.

By using these landscapes, they "maintained and amplified the pre-Columbian legacy," Junqueira said. "In a way, they're like guardians of this ancient footprint, and through their current practices, they're still adding complexity and heterogeneity to the forest."

But the caboclo farmers weren't necessarily seeking out the most fertile soil, he suspected. In part, people have kept using these anthropogenic forests for the reason humans have always chosen their homes: location, location, location. "The same criteria that people use today to choose an area to live, they also used in the past: high bluffs, just on the margin of the river, close to a clean water source."

That pattern is just what Schmidt and MIT geologist Samuel Goldberg and colleagues found in their own remote sensing and machine learning effort. By overlaying multiple bands of satellite imagery of the Xingu Indigenous territory, they could predict the areas of dark earths with reasonable accuracy.



"We found a widespread pattern of ADE deposits located on river bluff edges on the uplands adjacent to the floodplains," said Goldberg in a presentation at AGU's Fall Meeting 2021 (bit.ly/dark-earth-patterns).

In total, he said, the dark earths were predicted to cover 250–700 square kilometers, or up to 2.7% of the region. Multiplying this area by the carbon density and soil depths that have already been measured in field studies suggested that anthropogenic soils in the Xingu Indigenous territory could be sequestering 3–7 megatons of extra carbon in addition to the amount naturally stored in the soil.

ANTHROPOGENIC SOILS IN BRAZIL'S XINGU INDIGENOUS TERRITORY COULD BE SEQUESTERING 3–7 MEGATONS OF EXTRA CARBON.

Applying these densities to Amazonia as a whole—something Goldberg admitted is "simply speculation" at this stage—would mean that the dark earths of the Amazon could be locking up as much carbon as the amount emitted annually by the United States. Much more work needs to be done to find out whether that is really the case, said Goldberg, "but it does suggest that ADE could be a substantial reservoir of organic carbon in the soil."

Beautiful Biochar

As carbon dioxide (CO_2) accumulates dangerously in the atmosphere and nations struggle to feed growing populations sustainably, a technique that both sequesters carbon and improves soil for agriculture sounds like a silver bullet. And indeed, studies of terra preta have prompted a global research effort into the climate-mitigation potential of enriching soils with charcoal, creating a simplified modern analogue of dark earth, dubbed biochar.

Terra preta has "definitely been an inspiration" for biochar, said Johannes Lehmann, a biochar researcher and soil biogeochemist at Cornell University in Ithaca, N.Y., but the point is not to perfectly re-create it. The dark earths made by Indigenous Amazonians contain fish residues, manure, and ceramics, elements usually absent from biochar. Biochar has the focused goal of drawing down carbon dioxide from the atmosphere at the same time as improving agricultural yields.

The main technique to create biochar, called pyrolysis, involves charring waste vegetation at low temperatures in an environment with little to no oxygen. "If you starve it of oxygen, then you cannot oxidize a piece of wood to CO_2 and water—and you leave a lot of carbon behind," said Lehmann. The same piece of wood left to rot or burned in normal (oxygen-rich) conditions would release its carbon into the atmosphere within minutes to months. When vegetation is charred, the carbon remains trapped for decades or even centuries. "It is orders of magnitude more persistent."

Recent research has found that biochar improves the soil in some contexts and has the most climate mitigation potential of any land-based effort, including agroforestry and afforestation—though Lehmann pointed out that nothing is more effective than keeping forests standing in the first place. More than 300 firms are already producing commercial biochar products.

Still, it's early days for the industry. As a technology, biochar is about where photovoltaics were in the 1970s, Lehmann said. "In the '70s, we all said photovoltaics will save the day, and then it took 40 years until anything happened." Applying charcoal to soil might sound relatively simple—and indeed, it's one of the few mitigation measures that can be started right now—but more research and practical experimentation are needed to determine where and how it can have the greatest effect, he said.

Most important, farmers themselves have to see a benefit in biochar, said Lehmann. "I don't think we can expect an avocado grower to be a carbon farmer. If putting biochar on the avocado trees doesn't improve the avocados, then frankly I don't care whether it sequesters carbon. A land user will do it if she discovers that this is good for her soil."

Scaling up will take time, then. "That's the Achilles heel of a distributed system, right? It is more difficult to scale than a coal-fired power plant or an injection of CO_2 into a big hole. But it also has beauty. It's more robust once it's there, and it's likely more sustainable as it develops," Lehmann said. "The worst thing that can happen is we have a few million happy farmers but have not saved the climate. I call it a no-regret strategy."

Some researchers, however, have expressed concern that the commercialization of biochar could lead to illegal deforestation as biochar companies search for the cheapest raw materials to pyrolyze. In addition, biochar owes its existence to Indigenous Knowledges from Amazonian communities, they argue; if there are profits to be made, will Indigenous Peoples benefit?

Turning terra preta into a commodity could have implications for the Amazon's ancient sites, too. Archaeologists remain deliberately vague about the precise locations of dark earth to protect those sites, said McMichael. In some parts of Brazil, terra preta sites are already being mined for potting soil or bulldozed to build modern towns. "There are hundreds of archaeological sites with dark earth being destroyed as we speak," Schmidt said. "They're protected by law, but there's no enforcement."

And they're irreplaceable. Destroying these patches of precious earths entails a loss of history, of culture, of fertile cropland, and of biodiversity, Schmidt said. "Also, any carbon that's stored in those soils will be emitted to the atmosphere." The answer isn't to lock them up, though. The best way to preserve them, he suspects, is for traditional communities to keep living on them, farming them with low-impact tools that don't overly disturb the soil, and, through their actions, maintaining the millennia-old legacy of Amazonia's human past.

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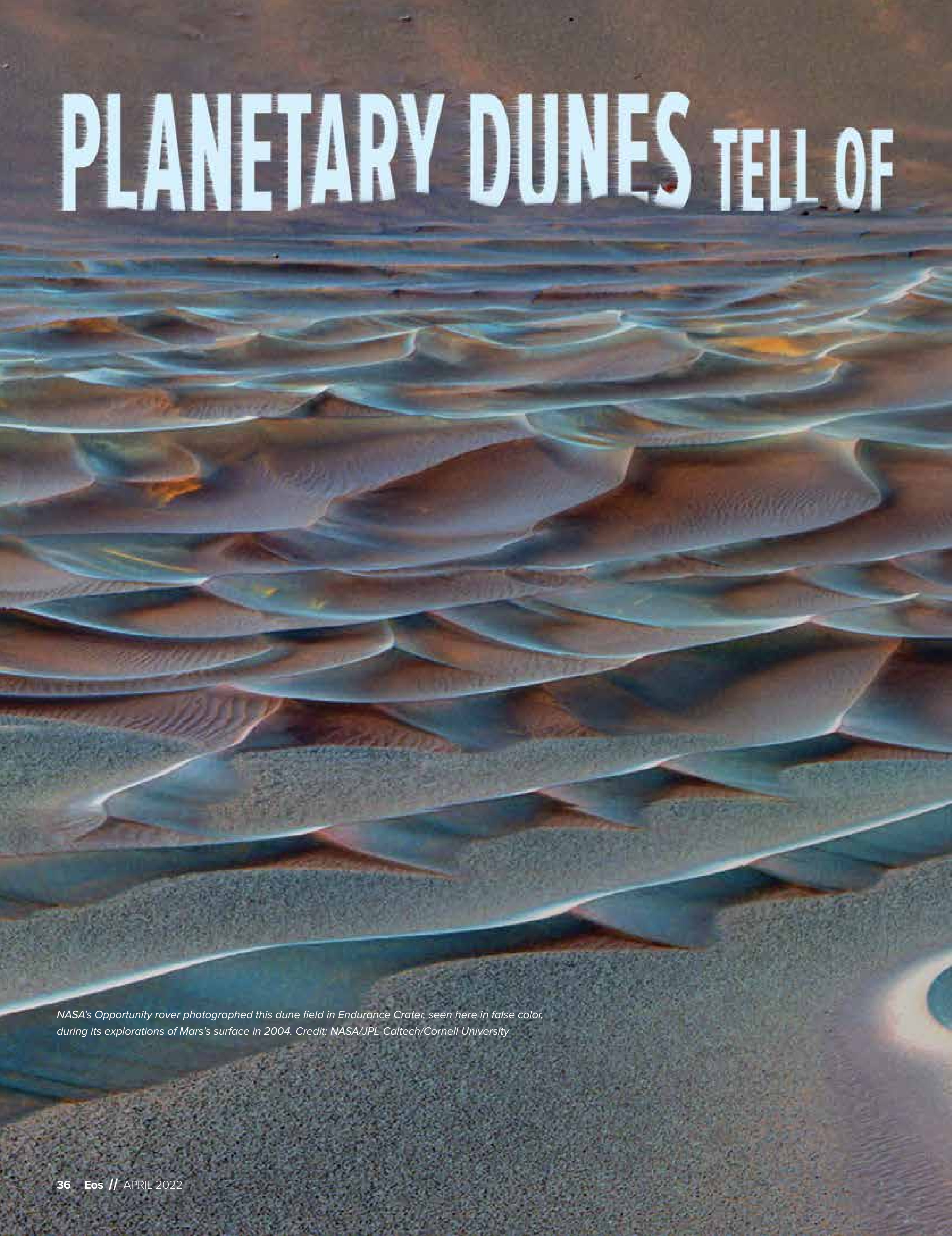
PLANETARY DUNES TELL OF



NASA's Opportunity rover photographed this dune field in Endurance Crater, seen here in false color, during its explorations of Mars's surface in 2004. Credit: NASA/JPL-Caltech/Cornell University

OTHERWORLDLY WINDS

By Timothy N. Titus, Serina Diniega, Lori K. Fenton, Lynn Neakrase, and James Zimbelman

On Earth and throughout our solar system, ripples and dunes in sand and dust offer insights into how winds blow, liquid currents flow, and solid particles fly and bounce over the terrain.

Dune fields are common on beaches and in deserts—think of the imposing sand hills and sinuous ripples of the Sahara in Africa or the Karakum in Central Asia, for example—as well as underwater on the beds of rivers, lakes, and oceans. The varied shapes, sizes, and orientations of both modern dunes and those preserved in the geologic record tell of the conditions under which they formed, particularly the strengths and patterns of winds and ocean currents. This information offers us valuable windows into environments and climates at different places and at different times in Earth's history.

The same is true of dunes off Earth, making these features especially interesting to scientists investigating planetary conditions and evolution elsewhere. In fact, the current inventory of known dune fields in the solar system exceeds 8,000, including evidence of aeolian activity on the surfaces of smaller planetary bodies with transient atmospheres.

On Mars, more than 4,000 fields displaying a wide variety of dune forms have been mapped. Dunes have been imaged in two fields on Venus. The Rosetta spacecraft observed dunelike features on the nucleus of comet 67P/Churyumov-Gerasimenko, where a tenuous and transient atmosphere—

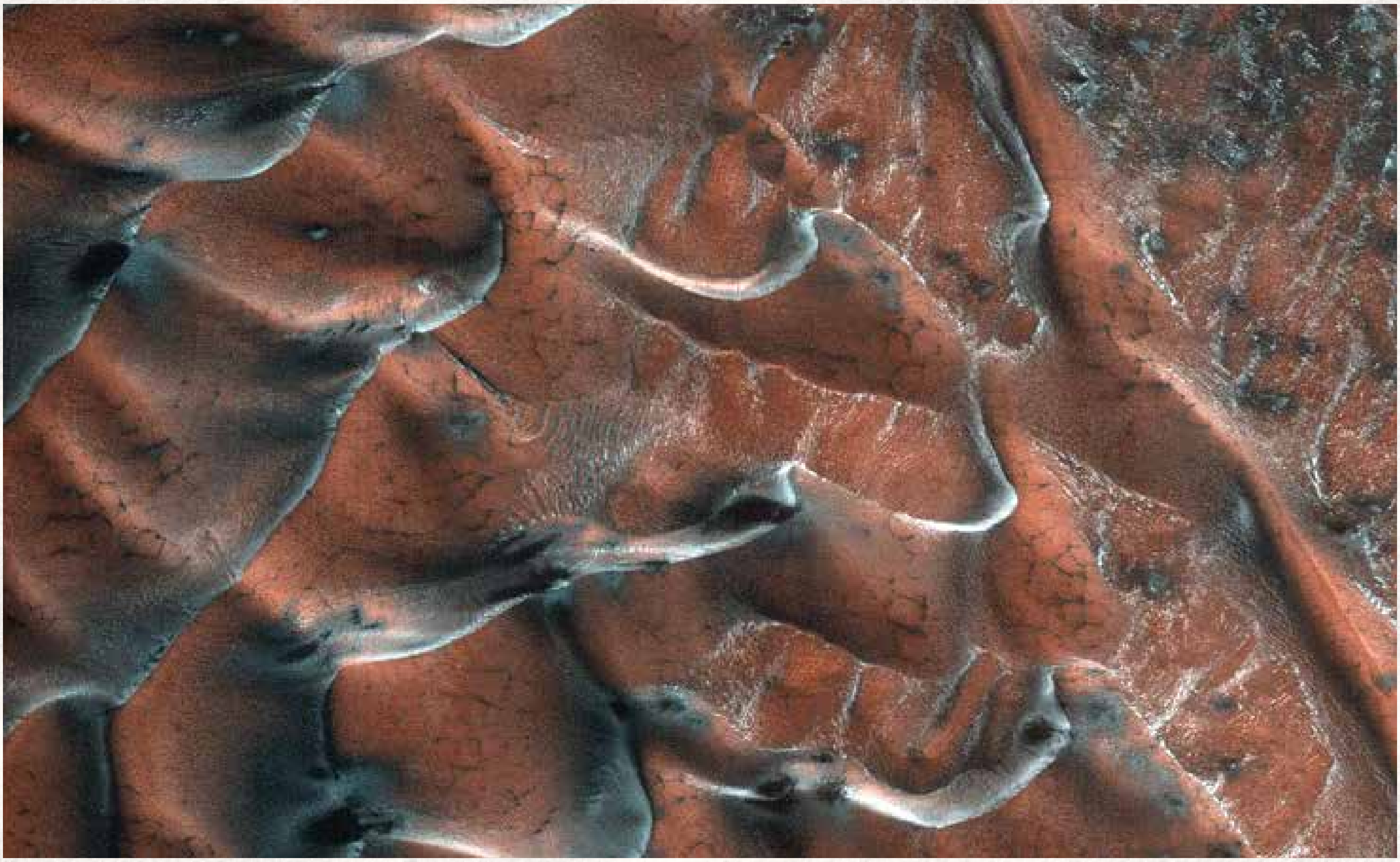
ON MARS, MORE THAN 4,000 FIELDS DISPLAYING A WIDE VARIETY OF DUNE FORMS HAVE BEEN MAPPED.

formed by vaporization of ice as the comet passes close to the Sun—may mobilize surface particles. Meanwhile, Titan, Saturn's largest satellite, has moon-circling longitudinal dunes near its equator; Triton, Neptune's largest moon, and Io, Jupiter's volcanically active moon, both have surface features indicating windblown sediment transport in transient atmospheres; and Pluto features dunelike forms on the frozen-nitrogen surface of Sputnik Planitia.

As exploratory missions continue to supply observations and as theoretical and technical advances emerge, the inventory of extraterrestrial dunes—and our understanding of how these features form in different environments—is sure to grow, offering more complete views of neighboring and distant worlds. Here we discuss the current state of knowledge about planetary dune processes and the need for future studies, including developments and ideas highlighted at (and since) the 6th International Planetary Dunes Workshop, held in 2020, that will inform the 2023-2032 National Academies of Sciences, Engineering, and Medicine's Planetary Science and Astrobiology Decadal Survey.

Blowing Dust and Bouncing Sand Grains

Most wind-mobilized, or aeolian, sediment grains can be placed into two broad categories: dust and sand. Dust is carried in sus-



Frost-tipped dunes in a crater on the northern plains of Mars are seen in this image taken by the High Resolution Imaging Science Experiment (HiRISE) camera on the Mars Reconnaissance Orbiter. Credit: NASA/JPL-Caltech/University of Arizona

A dust storm encroaches on dark north polar barchan dunes on Mars. Credit: ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO (bit.ly/ccbysa-igo-3-0)

pension and can be transported far from its origin. Sand is heavy enough that it either rolls along the ground or readily falls back to the surface after being lofted by winds, perhaps kicking up additional grains of sand and dust in a process called saltation. Saltating grains launch dust off the surface to form the atmospheric dust load (see sidebar), they abrade planetary surfaces to expose buried rock records, and they build bedforms that record wind patterns. Indeed, most aeolian landforms are associated with saltation.

On Earth, aeolian dunes can take on many shapes and sizes, such as parabolic, seif (or longitudinal), barchan, dome, or star. Many of these same forms have been observed elsewhere in the solar system. Barchan is the most common dune type on Mars, for example, whereas seif dunes dominate the equatorial regions of Titan. The morphology of Martian bull's-eye dunes is perhaps the most distinct from features known on Earth.

Aeolian ripples on Earth, formed by saltating (or impacting) grains of sand, have shapes similar to seif dunes but are much smaller and usually have a single well-defined slip face. This type of ripple also occurs on Mars, as does a second type of ripple formed from fluid drag, similar to ripples that form in riverbeds on Earth. These ripples are larger, more asymmetric, and more sinuous than impact ripples. Both types of ripples coexist on Mars's dry surface because the Martian atmosphere is thin, whereas Earth's thicker atmosphere allows impact ripples to overpower any formation of fluid drag ripples.

Dunes dwarf the Dragonfly lander on Titan in this artist's rendering. Credit: NASA/Johns Hopkins University Applied Physics Laboratory

Unmasking Venusian Dunes

Earth's two closest planetary neighbors, Venus and Mars, present opportunities to study sand, dust, and dunes under very different atmospheric conditions. Venus has a thick, opaque atmosphere of carbon dioxide and sulfuric acid that limits visual observation of the surface. The only two known dune fields on Venus were discovered in the early 1990s using radar data from the Magellan mission. Menat Undae, in the southern hemisphere, and Al-Uzza Undae in the northern hemisphere, span roughly 100 and 150 kilometers, respectively.

Why are there only two? Scientists have been working on this mystery for decades. Some have hypothesized that more dune fields exist but are not visible in the Magellan data, and others that the winds are too weak, even with the dense atmosphere, to cause saltation and form many dunes. Data from three new missions selected to go to Venus should greatly improve our understanding of the planet's surface and atmospheric conditions and help address this mystery. These missions—two radar-equipped orbiters (NASA's VERITAS, or Venus Emissivity, Radio Science, InSAR, Topography, and Spectroscopy; and the European Space Agency's EnVision) and a probe (NASA's DAVINCI+, or Deep Atmosphere Venus Investigation of Noble Gases, Chemistry, and Imaging Plus)—are all scheduled for launch late this decade or early in the next.

Monitoring Martian Dust

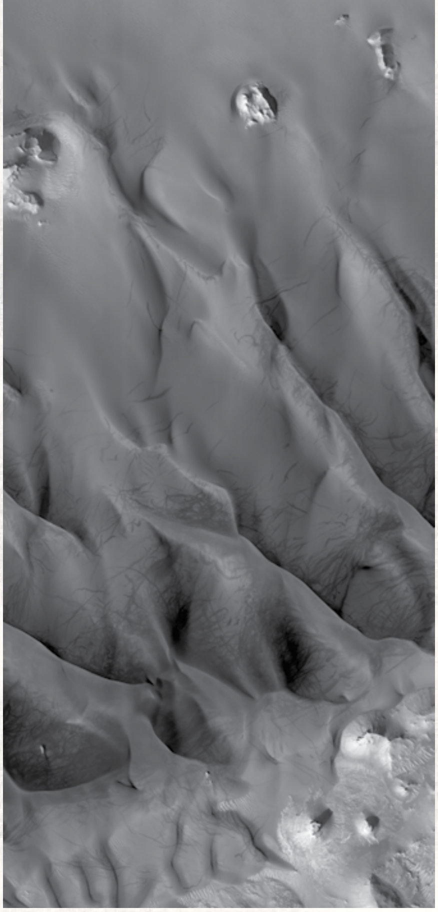
Among Earth's neighbors, only Titan and Mars are known to experience dust storms. On Mars, where we have abundant observations from orbit and on the surface, dust is thought to be lofted mainly via saltation, contributing to phenomena ranging in scale from meters-wide dust devils to global-scale dust storms.

In the absence of oceans or a significant hydrological cycle, variability in atmospheric dust loading largely dictates uneven heating of Mars's surface and atmosphere, and thus weather patterns and climate. Scientists must understand the distribution of atmospheric dust to produce reliable climate and forecasting models, which will be invaluable in identifying safe landing sites and predicting inclement weather for human missions to Mars.

Dust measurements from orbit, such as measurements that could be made by Doppler lidar, are thus needed to monitor Mars's atmospheric dynamics, wind speeds, and dust transport and identify major dust atmospheric pathways.

Studies of aeolian processes and dune formation mechanisms on Venus are relevant to the study of dune fields under thick atmospheres on other worlds, like Titan or some planets outside the solar system (e.g., most Earth-sized exoplanets discovered so far appear to have atmospheres and climates more like Venus's than Earth's). For example, if the Venus surface predominantly contains "microdunes" that were too small for the Magellan radar to resolve, future identification of these features along with detailed characterization of the Venusian atmosphere will elucidate microdune formation processes relevant to these other planetary bodies with thick atmospheres.

Furthermore, Venusian low wind velocities under high atmospheric pressure may be similar to ocean currents in terms of fluid flow and density. On Earth, ocean currents create dunelike bedforms as a result of water flowing over a surface of movable particles, and similar processes could occur in other places where bodies of liquid water or other fluids exist. Thus, Venus could represent an analogue for processes on both ocean worlds and exoplanets with thick atmospheres.



Dune fields exist on many bodies in our solar system, including on Mars, as seen in this image taken by HiRISE. Credit: NASA/University of Arizona

Aeolian Bedforms in a Low-Density Atmosphere

Mars has a much thinner atmosphere than Earth, and so provides an opportunity to study atmospheric conditions and aeolian processes intermediate between those on Earth and on bodies that lack atmospheres, like comets and Pluto. In addition, because Mars appears substantially more hospitable than most extraterrestrial bodies and thus is the aim for human planetary exploration, it is a prime target for acquiring in situ observations of active planetary surface-atmosphere processes.

Such observations could greatly advance the development of new models of aeolian processes that could be applied to other planetary bodies. Mars's atmospheric, surface, and environmental conditions are different from Earth's—enabling researchers to expand on existing models created on the basis of terrestrial data—but are still similar enough that terrestrial models remain a reasonable starting point.

Scientists have made solid progress in studies of aeolian processes on Mars by applying knowledge of terrestrial analogues, as well as with data from wind tunnel experiments and orbital and surface (i.e., rover) observations of Martian landforms and surface environments. For example, observed bedforms on Mars provide records of present and past winds, often showing the effects of multiple wind directions, which can be used to validate climate models.

A landed mission focused on studying Martian aeolian environments and processes would add to this progress by providing crucial ground truth for validating and improving the robustness of existing models for application to low-atmospheric-density regimes. Simulations could then be more confidently extended to model analogous processes operating within near-vacuum conditions like those on Pluto or on a comet. The flight-qualified instruments (e.g., for measuring sediment flux and wind speed profiles) and mission architectures needed to collect relevant in situ observations can feasibly be developed within the next decade.

Powered Flight on Alien Worlds

Powered flight enables detailed investigations of expansive, hard-to-reach dune fields on Earth, and the same would be true

An analogue field study shows dust devils at Smith Creek Valley in Nevada. Credit: Steve Metzger

Aeolian dunes spread out against a background of rugged mountains in Colorado's Great Sand Dunes National Park and Preserve. Credit: National Park Service

on other worlds. The successful flights of Ingenuity on Mars beginning in 2021, marking the advent of powered flight on another planet, may represent a defining moment in enhanced planetary dune exploration and science. Even though Ingenuity is primarily a technology demonstration, it has already conducted aerial reconnaissance for the Perseverance rover.

In addition to aerial reconnaissance, the next generation of Mars uncrewed aerial systems (UASs) should be designed to conduct in situ reconnaissance and characterization of dune fields. These tools offer the promise of much higher spatial resolution than is possible from orbit and the ability to explore the interiors of dune fields and other regions not reachable by ground transit. UASs could also support in situ analyses by rovers (e.g., by collecting samples and bringing them to the rovers) for more comprehensive investigations.

NASA's eight-bladed Dragonfly rotorcraft, scheduled to launch for Titan in 2027 and arrive in 2034, will carry a flying science package to the Saturnian moon. Dragonfly will land near the edge of Shangri-La—a large, dark region on Titan's surface—amid linear dunes seen in radar imagery collected by the Cassini spacecraft. Once there, it will determine the composition and grain sizes of the dune sediments, along with wind speeds and directions.

SCIENTISTS HAVE MADE SOLID PROGRESS IN STUDIES OF AEOLIAN PROCESSES ON MARS BY APPLYING KNOWLEDGE OF TERRESTRIAL ANALOGUES, AS WELL AS WITH DATA FROM WIND TUNNEL EXPERIMENTS AND ORBITAL AND SURFACE OBSERVATIONS.

The dune grain composition is of particular interest because the sediment is hypothesized to consist of complex organic compounds rather than silicate-derived debris as seen on Earth, Mars, and Venus. Titan's organics form in the atmosphere through irradiation of simple carbon and nitrogen compounds like methane and molecular nitrogen, but the mechanisms for forming sediment-sized particles on Titan remain unknown.

The Golden Age Is Afoot

As more data are acquired and more detailed computer models are used to dig into multiscale views of aeolian processes, improvements in data and model storage—both the content and the capacity stored—and access are needed.

Planetary aeolian studies rely on comparisons among data and insights from models, observations from analogue experiments conducted in the laboratory and in field environments on Earth, and spacecraft observations from other worlds. Whereas spacecraft observations are routinely archived in centralized data repositories, like the Planetary Data System, analogue data and output from aeolian and climate models are more commonly stored on individual or institutional servers, reducing the potential reuse of these results.

Data from analogue studies are increasingly being archived as the research com-

Dust devil tracks have removed dust from dark dunes on Mars in this HiRISE image. Credit: NASA/JPL/University of Arizona

RESEARCHERS ARE BEGINNING TO SUPPORT THE NOTION OF DEVELOPING A UNIFIED MODEL THAT ENCOMPASSES ALL OF THE CHARACTERISTIC SHAPES THAT FORM AT INTERFACES BETWEEN SANDY OR DUSTY SURFACES AND MOVING FLUIDS OBSERVED THROUGHOUT THE SOLAR SYSTEM.

munity has recognized the need to do so, and archiving policies are being modernized (e.g., requiring better metadata and metadata controls) to increase data searchability, accessibility, and usability. However, model outputs still are rarely considered data and often are not archived, in part because these outputs can be superseded rapidly as models are upgraded and model outputs are continually improved, making decisions of what should be saved and stored difficult. For example, should an output data set be archived every time an input parameter is tweaked and the model is rerun? If improvements are made to the model and all of the previous runs are redone, should all of those data be archived as well? If only selected outputs are saved, what standards (besides limitations on data storage space) should be applied to ensure a uniform curation process?

Conversations and ideas raised at the Planetary Dunes Workshop, and documented in white papers submitted for the Planetary Science and Astrobiology Decadal Survey 2023–2032, covered how best to handle modeling output and planetary analogue data (bit.ly/planetary-white-papers). And a recent NASA report incorporating research community input suggested that repositories be designated for both analogue data and model outputs. The same report emphasized the need to improve data discoverability, accessibility, and usability across all data types, regardless of where they are archived (go.nasa.gov/3HDBosd).

In addition to considerations of data, researchers are beginning to support the notion of developing a unified model of bedform morphology, one encompassing all of the characteristic shapes that form at interfaces between sandy or dusty surfaces and moving fluids observed throughout the solar system.

Until the past 15 years, models of bedform morphology were largely treated separately depending on the environmental conditions under which they formed. This paradigm started to change after Philippe Claudin and Bruno Andreotti demonstrated a consistent relationship explaining the wavelengths of a range of aeolian features, including Venusian microdunes and aeolian dunes on Earth and Mars (bit.ly/scaling-law-dunes). A unified framework would be invaluable for consistently interpreting the modern and former environments in which aeolian bedforms are built, offering us clearer views of past, present, and maybe even future conditions on Earth and other planetary bodies.

The next 2 decades will be an exciting time for planetary dune research. Indeed, with extensive continuing studies of Mars's varied aeolian systems, Ingenuity's and Dragonfly's flights, and multiple Venus missions, researchers may look back on this period as the golden age of the field.

Acknowledgments

We thank the Lunar and Planetary Institute for logistics and program support. The work by S.D. was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract 80NM0018D0004 with NASA. The work by L.K.F. was supported by a NASA Solar System Workings Program grant (80NSSC19K0025). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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▶ Read the article at bit.ly/Eos-planetary-dunes

Drop in Rain Forest Productivity Could Speed Future Climate Change

Tropical forests host a rich variety of plant and animal life and process vast amounts of carbon dioxide (CO_2). Therefore, researchers have been particularly interested in how these ecosystems might be affected by climate change. Some have hypothesized that the rise in atmospheric CO_2 is promoting carbon uptake by these forests, making them important carbon sinks. Evidence is mounting, however, that the balance of cost and benefit is reaching a tipping point, and global warming will soon hinder tropical forests' ability to soak up carbon.

In a new study, *Clark et al.* assessed tropical forests' annual net primary productivity from 1997 to 2018. They measured wood growth and litterfall in 18 plots in Costa Rica's La Selva Biological Station. The scientists collected litterfall every other week from basket traps and annually measured the growth of all live stems greater than 10 centimeters in diameter. They found that the stress associated with hotter temperatures outweighed the benefits of increased carbon dioxide. Annual aboveground net primary production fluctuated greatly from year to year, but no productivity component increased over the 21 years. Twig litterfall declined, and wood production suffered in years with slightly warmer nights and particularly hot dry seasons.

The new research provides further evidence that as nighttime temperatures continue rising and as more daytime hours exceed the optimum temperature for photosynthesis, productivity will decline. The authors warn that tropical forests could soon enter a positive feedback loop that will accelerate both global warming and tropical forest decline. As forests become less productive because of rising temperatures, they will soak up less carbon dioxide, which in turn will lead to more warming. This cycle could pose a major threat to the survival of these highly biodiverse ecosystems. (*Journal of Geophysical Research: Biogeosciences*, https://doi.org/10.1029/2021JG006557, 2021) **—Rachel Fritts,** *Science Writer*

Radiometric Dating Sheds Light on Tectonic Debate

At the far edges of continents, where the continental shelf transitions into the deep ocean, continental and oceanic plates come face to face. At many of these margins, the denser oceanic plate is pushed below the continental plate in a process called subduction. However, in some cases the oceanic plate ends up atop the more buoyant continental plate instead of diving below it, a process known as obduction.

Obduction zones are unique because they foster the recycling of surface continental material to the deep mantle, which happens infrequently, and they have formed almost exclusively in the past 1 billion years of Earth's history. The resulting ophiolites—slices of oceanic crust and mantle atop a continental plate—offer uncommon opportunities to view seafloor geology from the comfort of land.

The Samail Ophiolite (Oman–United Arab Emirates), in the northeastern corner of the Arabian Peninsula, is frequently studied as a model of obduction because of its well-exposed and well-studied geology. However, geologists disagree about the timing and geometry of the continental subduction that led to the final emplacement of the ophiolite. Several tectonic models offer hypotheses on the ophiolite's obduction but differ in their conclusions.

In a new study, *Garber et al.* sought to clarify the timing of the obduction episode in Oman. The authors sampled several different rocks from As Sifah, an Omani beach with an outcrop of high-grade continental metamorphic rocks once subducted beneath the ophiolite before they returned to the surface. The studied As Sifah rocks reflect a diverse range of lithologies that show that all experienced the same metamorphic evolution, the authors say. Samarium-neodymium (Sm-Nd) and uranium-lead (U-Pb) radiometric dating on the garnet, zircon, and rutile crystals in the rocks helped determine the age of the subduction event.

This beach at As Sifah, Oman has rocks that belie previously published estimates of the timing of the region's tectonics. Credit: Ji-Elle, CC BY-SA 3.0 (bit.ly/ccbysa3-0)

The findings provide new constraints on the timing of the obduction of ophiolitic rocks in Oman. The results indicate that the episode occurred approximately 81–77 million years ago when the Arabian continental plate subducted to the northeast below the Samail Ophiolite. The subduction of the Arabian plate to mantle depths occurred at rates similar to those of other small continental subduction events, and the tectonic evolution appears to be similar to that of other ophiolite formations.

This conclusion refutes previously published estimates that continental subduction in Oman started 110 million years ago and may have occurred over two distinct episodes. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB022715, 2021)
—Aaron Sidder, *Science Writer*

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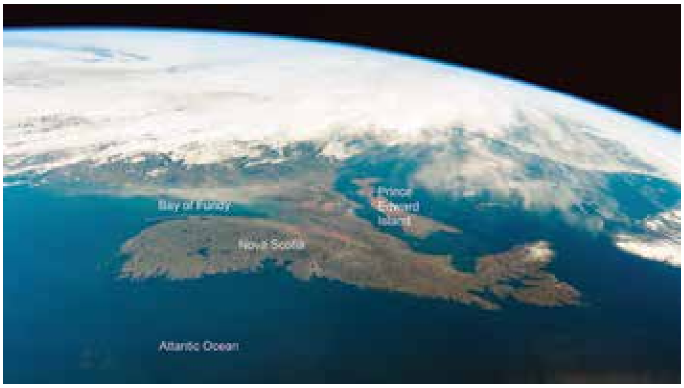
The Role of Magma in the Birth of the Atlantic Ocean



An advanced data analysis approach reveals that magmatism accompanied continental breakup at the magma-poor Nova Scotia margin, pictured here. Credit: NASA Earth Observatory

The Atlantic Ocean was born roughly 200 million years ago when the supercontinent Pangaea began to break apart. As continental crust stretched and fractured, oceanic crust took its place. To investigate this rifting process, scientists can analyze the structure of the present-day eastern North American margin, where North America and the Atlantic Ocean meet. The composition of the crust and upper mantle provides clues about geological processes that accompanied continental breakup.

One important activity in this process is magmatism. For example, the portion of the North American margin associated with the eastern United States has thick sections of igneous rock that classify it as magma-rich. However, there are also magma-poor parts of the margin offshore of Nova Scotia and Newfoundland. Using an advanced data analysis approach, *Jian et al.* developed a high-resolution seismic model to investigate the magma-poor Nova Scotia margin.

The team used a technique known as full-wave inversion to analyze seismic waves captured by 78 ocean bottom seismometers in response to pulses from an array of air guns. By including all the information in the seismic waveforms, the researchers created a high-resolution velocity model that was used to produce a detailed image showing how seismic waves were reflected at different positions and depths.

On the basis of these data, Jian and colleagues identified distinct domains across the margin, representing stages of rift formation. They uncovered features suggesting that a magmatic event accompanied the final continental breakup at the Nova Scotia margin. This event forms a boundary between thinned continental crust and oceanic crust.

These results provide a new picture about what happened in a region off northeastern Nova Scotia that has been thought to be amagmatic. The findings support evidence of a role for magmatism in continental breakup at magma-poor margins elsewhere as well. (*Journal of Geophysical Research: Solid Earth*, https://doi.org/10.1029/2021JB022201, 2021) **—Jack Lee,** *Science Writer*

Rising Trend Predicted for Conditions Linked to Severe Storms

As Earth warms in the way scientists predict, extreme precipitation events will increase. However, predictions are less certain as to whether a similar global uptick will occur for severe thunderstorms, which can produce extreme winds, tornadoes, and hailstorms that destroy crops and property.

Building on previous research, *Lepore et al.* report new climate model predictions suggesting that conditions associated with severe storms will arise up to 20% more often worldwide for each 1°C of global warming—perhaps also resulting in an increase in severe storms. The authors suggest that scientists attempting to forecast severe storms in a future climate can consider atmospheric conditions that are favorable to these storms, even if the conditions do not always lead to them. Also known as severe weather proxies, such conditions involve several factors, such as wind shear and atmospheric instability.

This new research combines several different methods for computing severe weather proxies to account for a wider range of possibilities. The researchers calculated these quantities from seven different global climate models developed under the current phase of the Coupled Model Intercomparison Project (CMIP6) to evaluate how the frequency of conditions associated with severe storms might change under different warming scenarios.

Because this approach at this scale is still very computationally complex, the researchers developed a novel way to process huge amounts of CMIP6 data using the Pangeo cloud computing platform.

The analysis suggests that around the world, severe weather conditions will arise 5%–20% more often per 1°C of global temperature rise, primarily because of increased atmospheric instability. However, because severe storms do not always arise despite favorable conditions, any associated increase in severe storms themselves is expected to be smaller. Compared with other regions, the Northern Hemisphere is predicted to experience the biggest increase in convective environments.

Future research could build on these findings by reducing remaining uncertainties in climate simulations, addressing severe storm predictions on the scale of individual regions or seasons, and refining the new Pangeo-based computing approach, the authors say. (*Earth's Future*, https://doi.org/10.1029/2021EF002277, 2021) **—Sarah Stanley,** *Science Writer*

Amazon Deforestation and Fires Are a Hazard to Public Health

Wildfires are increasingly common, and their smoky emissions can wreak havoc on human health. In South America, fires may cause nearly 17,000 otherwise avoidable deaths each year. Fire frequency in the Amazon basin has been linked to climate—drier conditions result in more fires—but direct human action, such as deforestation, drives up fire frequency as well.

A clearing smokes after a forest fire in Brazil in 2017. Credit: Felipe Werneck/Ibama, CC BY 2.0 (bit.ly/ccby2-0)

Deforestation resulting from humans burning vegetation can cause wildfires that spread out of control. Smoke from these fires also interacts with clouds and sunlight to reduce rainfall, which creates dry, fire-prone conditions. Perhaps its most subtle impact is that deforestation breaks up the massive rain forest ecosystem, disrupting the forest's effect on climate and creating a drier environment with greater fire risk.

The number of fires—and the amount of fire-generated air pollution—in the Brazilian Legal Amazon (the nine states in Brazil's Amazon basin) has closely shadowed the deforestation rate over the past 2 decades. In the early 2000s, high deforestation rates led to frequent fires and accompanying air pollution. Over time, the Brazilian government enacted policies to protect large sections of the rain forest, and the deforestation rate dropped. In the past decade or so, however, the rate of deforestation has been slowly climbing again, bringing with it increased fire and health risks.

In a new study, *Butt et al.* model the year 2019 under different deforestation scenarios to understand the link between these events in the rain forest and public health.

The researchers found that if 2019 had matched the year in the past 2 decades with the least deforestation, regional air pollution would have been substantially lower that year, resulting in 3,400 fewer premature deaths across South America. If, on the other hand, deforestation rates in 2019 had matched those of the early 2000s, before government regulations brought the rates down, the number of fires would have increased by 130%, and the number of deaths would have more than doubled to 7,900.

These models demonstrate the link between direct human action (such as deforestation) and environmental hazards—and consequently, public health. They also, the authors said, show how government environmental protections can have a substantial impact on human health. (*GeoHealth,* https://doi.org/10.1029/2021GH000429, 2021)
—Elizabeth Thompson, *Science Writer*

Diurnal Oxidation for Manganese Minerals in the Arctic Ocean

Manganese is an important element for all life, but it plays an especially critical role in photosynthesis, in which it is the catalyst for splitting oxygen molecules from water. In the ocean—where phytoplankton are a key source of photosynthesis—manganese exists in three oxidation states: Mn(II), Mn(III), and Mn(IV).

In the Mn(II) state, manganese is quite soluble and can be used by phytoplankton as a micronutrient for photosynthesis. In the Mn(IV) state, it forms highly reactive solid-phase manganese minerals that can act as a sponge to remove other elements from solution. Understanding the relative abundance of manganese oxidation states tells us which of these important roles manganese is playing. Past studies in low-latitude oceans have pointed to diurnal variations in the relative abundance of the various oxidation states in the near-surface ocean layer.

In a new study, *Xiang et al.* explore the cyclical nature of manganese oxidation state abundances using samples collected during a 2015 GEOTRACES cruise in the Arctic Ocean. The authors attempted to identify diurnal changes in the Arctic using synchrotron-based X-ray absorption spectroscopy. Micrometer-sized manganese particulates were extracted from seawater pumped from the survey vessel at an ocean depth of roughly 20 meters, where sunlight can reach during the daytime. The researchers then analyzed 13 samples covering a range of local times.

From the spectroscopy results, the authors estimated the average oxidation state of each sample and correlated that with the available light at the time of sample collection. One complicating factor in the Arctic are the 24-hour days and 24-hour nights during some parts of the year. The 13 samples were split into four groups corresponding to whether they were collected during the day or the night and whether there was a diurnal sunlight cycle at the time.

The authors' analysis found that the most oxidized samples were collected during darkness, and the least oxidized ones were collected during the day. Specifically, the average oxidation state was less than 2.4 for samples collected in light and greater than 3.0 for samples taken in darkness. Although the total number of samples studied was relatively small, this is compelling evidence for the existence of a diurnal cycle in the oxidation state. As manganese can be a key micronutrient for photosynthesis-based ecosystems in its reduced state and acts like a sponge in its oxidized state, this observation may have important implications for biological and chemical cycling during times of extreme light or darkness in the Arctic. (*Geophysical Research Letters*, https://doi.org/10.1029/2021GL094805, 2021) **—Morgan Rehnberg,** *Science Writer*

Converting Auroral Observations into 3D Structures

A persistent obstacle to a more complete understanding of Earth's auroral activity is characterizing the structure of auroral arcs in 3D. In situ methods, such as spacecraft transits, can directly observe only a narrow slice of the phenomenon, whereas ground-based images compress the dimensionality into their plane of observation.

Clayton et al. present a new technique that aims to overcome these difficulties by using various observations as constraints for a physical model that then provides a 3D estimate of the feature's structure. The research team then demonstrated the approach's ability to describe kilometer-scale plasma structures in the vicinity of an actual auroral arc.

The new technique is built around the Geospace Environment Model of Ion-Neutral Interactions (GEMINI), a 3D ionospheric model. This model is driven with two distinct data sources: particle fluxes and electric field measurements. The particle data are derived from inversions of ground-based images, whereas the field data can be taken from in situ spacecraft observations or from ground-based radar.

An Isinglass sounding rocket launches from Poker Flat, Alaska, to gather data from an auroral arc. Credit: Merrick Peirce

The study uses data from a 2017 sounding rocket launch. In situ data are in the form of a 1D line of observed values corresponding to the flight path of the rocket. A key step in the process is converting these data, which cut across the model grid, into a 2D estimate of the plasma flow. Clayton and colleagues present two methods for accomplishing this and compare their relative performances.

Once the data are prepared, GEMINI is run to generate several 3D, time-varying outputs, including the plasma currents and densities. Constrained by the initial measured data, these outputs are representative of the actual physical structures surrounding the auroral arc. According to the authors, their work demonstrates that they can glean insight into the relative strength of various physical processes in an auroral environment. (*Journal of Geophysical Research: Space Physics*, https://doi.org/10.1029/2021JA029749, 2021) **—Morgan Rehnberg,** *Science Writer*

Recovering Mantle Memories from River Profiles

The continent of Africa has distinctive physical geography—with an "egg carton" pattern of basins and swells—that researchers attribute to plumes of mantle rocks rising beneath a tectonic plate. Marine fossils on mountaintops in African and Arabian deserts suggest that until about 30 million years ago, those portions of the landscape were at or below sea level. But the spatial and temporal evolution of this uplift process is still not well defined. In a new study, *O'Malley et al.* use the profiles of the continents' major rivers to trace the evolution of the landscape in space and time.

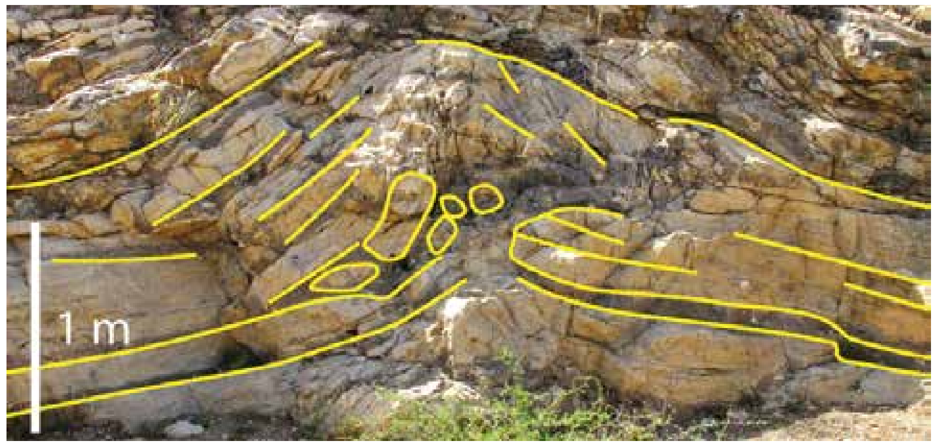
To test the idea that rivers might serve as "tape recorders" for mantle processes, the researchers focused on Africa, Arabia, and Madagascar, where regional uplift patterns during the Cenozoic are relatively well constrained. They applied a closed-loop modeling strategy that involved inverting more than 4,000 river profiles to recover signals of regional uplift and validating those signals with geological observations.

The team used dynamic forward landscape simulations to evaluate the influence of such factors as precipitation and drainage divide migration, as well as to test the assumptions used in the inverse modeling of river profiles. Although these assumptions are still a matter of debate, this study showed that inverse modeling of river profiles across the study area recovers an uplift history that fits observations, and landscape simulations using these uplift histories predict drainage networks, paleotopography, and deltaic sedimentation histories that match data. This result remains true when precipitation rates vary across space and time. Overall, the study suggests that calibrated inverse modeling of river profiles can be successfully used to study landscape evolution. (*Journal of Geophysical Research: Earth Surface*, https://doi.org/10.1029/2021JF006345, 2021) **—Kate Wheeling,** *Science Writer*

New research uses profiles of major rivers, like the Nile, pictured here, to trace the history of uplift across the African continent. Credit: Vaido Otsar, CC BY-SA 4.0 (bit.ly/sa4-0)

Sedimentary Tepees Record Ocean Chemistry

The ocean is an important reservoir in Earth's carbon cycle and presently is a sink for atmospheric carbon. The export of carbonate from the ocean to sediment depends on ocean chemistry, which is influenced by tectonic events such as mountain building and by calcareous organisms that change and evolve over geological timescales, among other factors. The balance of these factors controls carbonate concentrations in the oceans and is recorded in seafloor sediments. *Smith et al.* provide an important contribution to our understanding of past ocean chemistry with the development of new proxies for carbonate chemistry from carbonate facies and sedimentary textures preserved in the geologic record, specifically tepee structures and pisoids, in arid coastal environments. The authors demonstrate that the presence of these proxies is consistent with a rapid expansion of calcifying organisms in the mid-Mesozoic. Of note, they also show that the proxies are among the few that provide insight into ocean chemistry in deep time, as far back as the Precambrian. (https://doi.org/10.1029/2021AV000386, 2021) **—Vincent Salters**

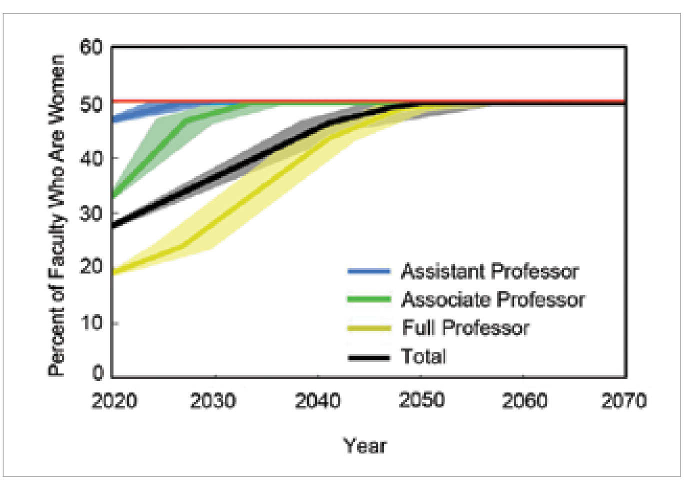


Tepee structures in this Middle Permian arid coastal facies from the Delaware Basin in the United States are outlined in yellow. The scale of the structures is much larger than recent analogues. Credit: Smith et al.

Steady but Slow Progress on the Long Road Toward Gender Parity

Diversity among scientists expands the questions our science asks, the approaches it takes, and the quality and impact of its products. Unfortunately, the geosciences have one of the worst records of diversity among their ranks. Progress is being made to include more women in the geosciences, but *Ranganathan et al.* show that assuming equity in hiring and retention going forward, gender parity in the geosciences at U.S. universities will not be reached until 2028, 2035, and 2056 for assistant, associate, and full professors, respectively. Women of color and all minoritized groups face a longer road to inclusion.

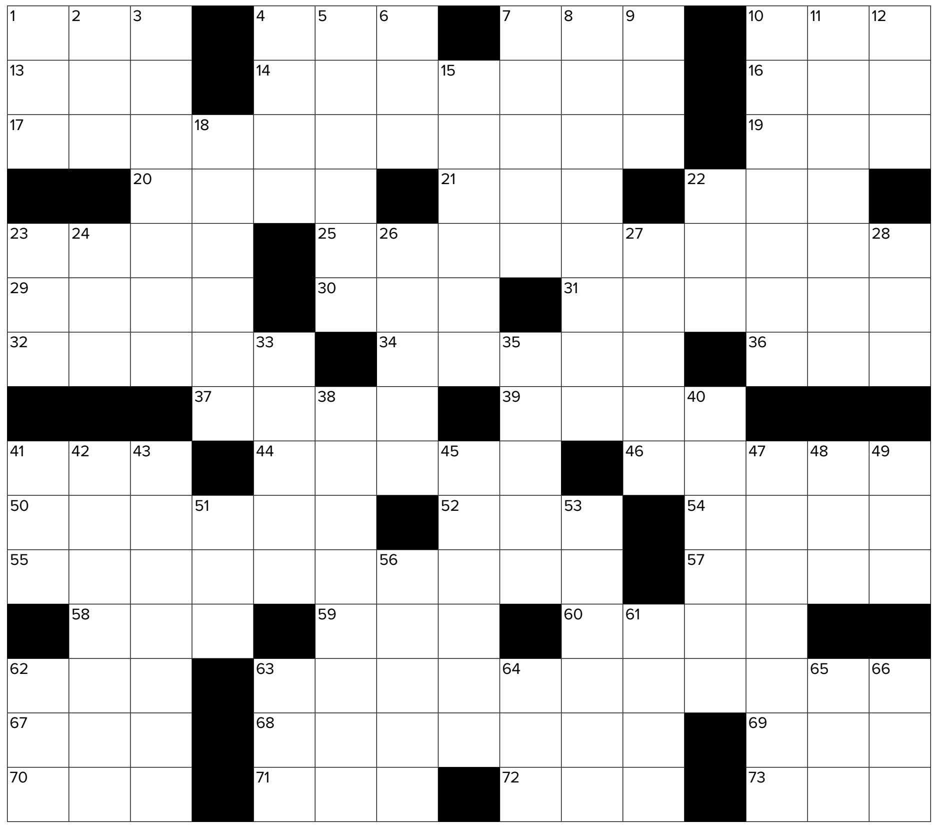
In an accompanying Viewpoint, *Hastings* shares the policies, institutional support, and community support that helped her overcome several obstacles in her career. These data and personal stories show that actions have made a difference and will continue to do so, but institutions and their leaders need to pick up the pace to make the geosciences more inclusive and equitable. (https://doi.org/10.1029/2021AV000436 and https://doi.org/10.1029/2021AV000514, 2021) **—Eric Davidson**



The authors use historical data and a model to project future gender distribution in the geosciences at U.S. universities. Their analysis suggests that gender parity has nearly been reached for assistant professors, but it will come much later for those in more advanced career stages. The model projections assume that faculty are hired at a 1:1 gender ratio and that there is equal retention between men and women, assumptions that are not yet assured. Credit: Ranganathan et al.

Greenhouse Connection

By Russ Colson, Minnesota State University Moorhead



ACROSS

1 Celestial object usually smaller than a dwarf plan.
4 Perfectly suited
7 Measure of a student's success
10 Shelter from dust on a tractor
13 After a bee?
14 Wrestled
16 Ending for di- or ge-
17 Made of the theme material and erupted from a volcano
19 A stimulating plant in Arabia
20 Arterial branches
21 Last three letters in the name of a western Arabian country and of that country's capital
22 Young coyote
23 (At a) great distance
25 Made of the theme material and deposited where rain drips into a cavern
29 What each of the CO_2-containing theme entries is
30 Perhaps 110°, meteorologically
31 Whiled away the hours dreamily
32 Slow deformation of soil on a slope
34 One of the two most abundant greenhouse gases (along with a component from the theme material)
36 Not subtract
37 Hoodwink
39 As simple as that abbv.
41 Might find at a hot spring?
44 There's a whole House of them in the United Kingdom
46 Not a winner
50 Made of the theme material and formed in the hearts of mountains
52 Seventh Greek letter
54 Made of the theme material where springs enter an alkaline lake
55 Made of the theme material and often forming cliffs in arid climates
57 Ending for ten-, peas-, and page-
58 Key consideration in global warming, with infra _____
59 Hoppy beer
60 Afflicts
62 Not max
63 Crystal made of the theme material and once used by Vikings for navigation
67 *Star Wars* bad guy as a child
68 Of a marriage
69 Unity
70 Geospatial intelligence agency within the U.S. Dept. of Defense, or *Star Wars* filming location Phang _____ Bay
71 Mostly underwater, if world glaciers melted (abbr.)
72 Perhaps 110°, geographically
73 Faucet

DOWN

1 Basketball power conf.
2 Important reservoir for heat and CO_2
3 A depositional or erosional landscape step
4 Smallest unit of an element
5 Penalize for a crime
6 Flight policing org.
7 Cells that protect neurons
8 Spot, Bandit, Kitty, and Fluffy
9 Fruity drink
10 A hash of shells made of the theme material
11 What surviving creatures did after the Permian
12 Wager
15 Geological layers
18 Like most trees—or what the dog did
22 Time sheet time off
23 A rainbow, for example
24 Start for -bid or -bear
26 Shape of cumulus congestus cloud
27 Made of the theme material extracted by jellyfish relatives
28 Terminal teacher deg.
33 Not pushes
35 Preference
38 Lyrical
40 Sums
41 Three shirt sizes
42 Creating a duo
43 Landlocked nation between the Caspian and Black seas
45 Highest peak in North America
47 Magnetic perturbation on a near star
48 Young newt
49 Dorm monitors
51 Breeding area, as an oyster _____
53 Sun salutations, for example
56 *The Pirates of Penzance*, for one
61 Run at low power
62 Classic *Twilight Zone* episode "To Serve _____"—it was a cookbook
63 World lending org.
64 Consumed
65 Common answer to a professor's question, "What do you hope to get out of this class?"
66 One of 435 in the House

See p. 43 for the solution.

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AMS American Meteorological Society

APHA American Public Health Association *For science. For action. For health.*

Citizen Science Association

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